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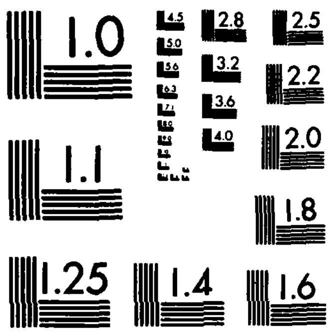

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PREVENTIVE MAINTENANCE INTERVALS
FOR COMPONENTS OF THE
F-15/F100 AIRCRAFT ENGINE

John R. Brill, Captain, USAF

LSSR 93-83

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Costs of maintenance can be reduced for many engine components by replacement before failure. This has been one objective of the Air Force Reliability Centered Maintenance (RCM) program. The key to realizing cost savings is optimization of the replacement or inspection interval. Graphic solution techniques show promise as a simple, consistent, and valid method of interval determination. They are based on use of actual age-at-failure data and cost data for individual parts of an engine, such as fuel pump or rotor disc. This study illustrates a graphic method of determining their replacement intervals, using five components of the F100/F-15 aircraft engine as a case study. The resultant optimum intervals and expected costs differ up to fifty percent from methods where actual costs and actual ages-at-failure are not used. Graphic analysis is a quick method responsive to system changes, but depends on use of representative age-at-failure data. This study verifies a basic technique. Existing methods can be used to aggregate the set of intervals into an engine maintenance plan.

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PREVENTIVE MAINTENANCE INTERVALS FOR COMPONENTS OF THE F-15/F100 AIRCRAFT ENGINE

A Thesis

Presented to the Faculty of the School

of Systems and Logistics

of the Air Force Institute of Technology

Air University

In partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Management

By

John R. Brill, BSME
Captain, USAF

September 1983

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This thesis, written by

Captain John R. Brill

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS MANAGEMENT

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CHAPTER 1

F100 ENGINE MAINTENANCE

The turbine engine is often the single most expensive subsystem of a jet aircraft. A 1980 study by the General Accounting Office (GAO) estimates that afterburning engines in attack and fighter aircraft account for thirty percent of the aircraft life cycle cost, and the fuel they consume accounts for another ten percent (10:7). The present Air Force engine inventory includes about 23,000 engines, representing a $13 billion investment and more than $700 million per year in operations and support costs (37).

The F100 Engine

The most complex and expensive of these engines is the F100 twin-spool, augmented turbofan, shown in Figure 1. It is the original power plant for the F-15 and F-16 aircraft. The F100 is designed to include the five separable modules of Figure 1(a). These are inlet/fan, core engine, fan drive turbine, augmentor/nozzle, and gearbox. Lifetimes for each engine and its modules are separately tracked, since they have different life characteristics. Figure 1(b) shows the engine arrangement. Inlet air is compressed by the fan, then passes through the core engine, where it is compressed, burned, and deflects through a turbine which

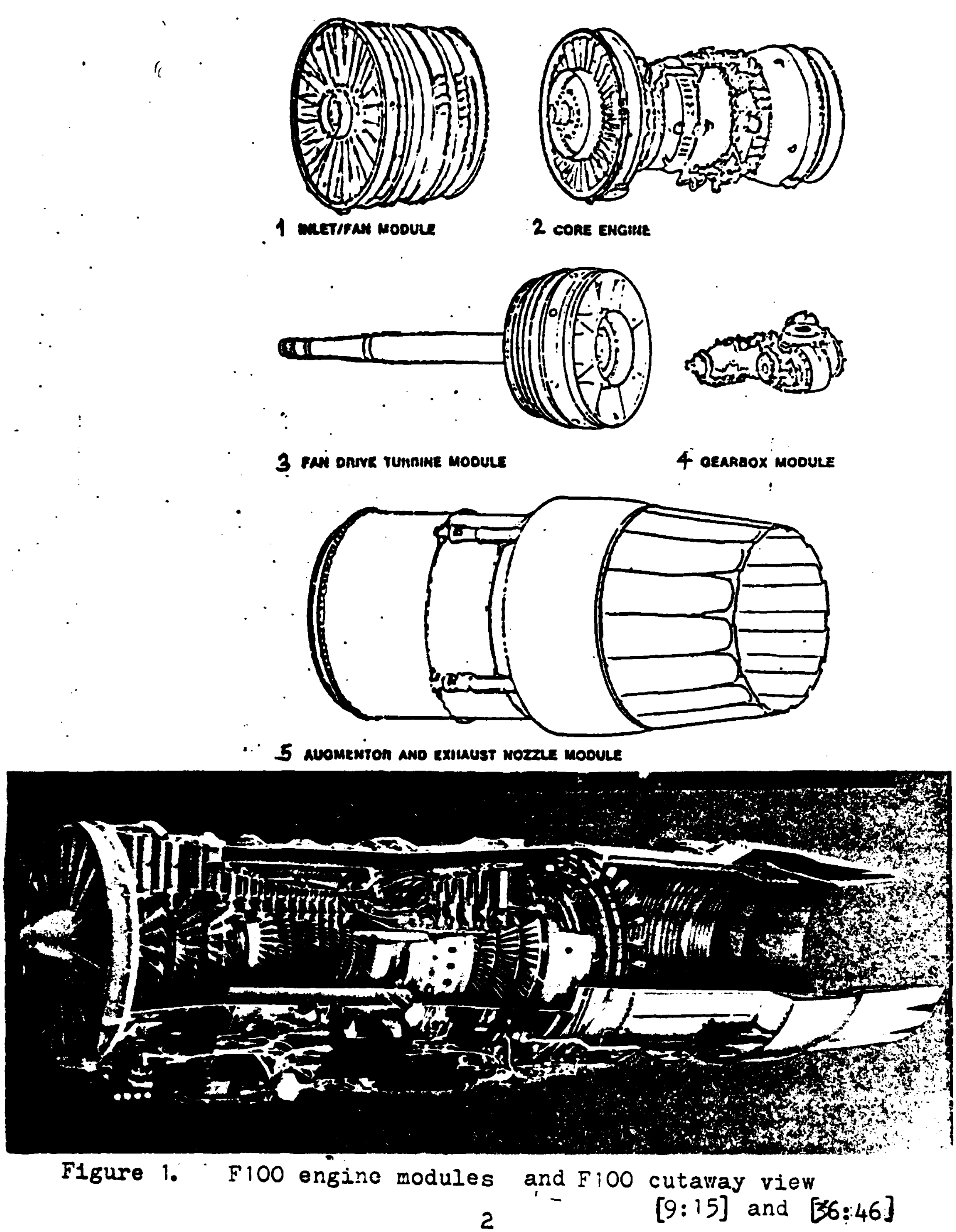


Figure 1. F100 engine modules and F100 cutaway view [9:15] and [36:46]

drives the core compressor. The exhaust then exits through the fan drive turbine, augmentor, and variable nozzle. Components of other engine subsystems can be seen on the engine exterior. These include controls for fuel and airflow, gearbox and lubrication, fuel delivery and electrical power/ignition. With the augmentor in operation, the 3000 pound F100 produces 23,000+ pounds of thrust at sea level.

F100 Engine Costs

These engine capabilities have not been cheap to acquire and support. F100 acquisition cost has averaged about $2 million per engine. But continuing operations and support costs for the F100 have exceeded 2400 dollars per flying hour since 1979 (37, 38), surpassing acquisition costs in less than 850 flying hours. At present flying rates, this is about $400 million dollars per year, eighty percent of it in spare (replacement) engines, modules, and parts.

The F100 also has significant readiness impact. Based on 1979-82 Air Force data studies in this project, the F100 accounted for about eight percent of total F-15 aircraft down hours and one million base maintenance labor hours per year (including inspections). With cost and readiness impacts of this magnitude, small percentage improvements could have large benefit. Consequently, many ways have been explored to improve the cost-effectiveness

of F100 preventive maintenance.

F100 Preventive Maintenance Requirements

Engine design and test methods, actuarial analysis, age exploration, reliability centered maintenance (RCM), and cost modeling have all played a part in defining preventive inspection and replacement policies for the F100 engine.

Engine Design and Test Methods

Through the first several years of engine deployment, the engine design and usage may change rapidly, requiring frequent revision of maintenance policies. The drivers of preventive maintenance requirements during this phase are engine structural life properties and the mission profile, as developed and verified in the Engine Structural Integrity Program (ENSIP). The ENSIP program provides information on expected life properties of the major engine parts, and identifies the parts requiring safety age limits (6:1). These are usually set based on a three-sigma (99.9 percent) probability of survival, or a maximum acceptable mishap risk per 100,000 flying hours. ENSIP provides the initial coefficients which relate component life to its operating time, start/stop cycles, and low cycle fatique (LCF cycles). The engineering analyses which identify life properties and failure criteria include the Reliability Analysis (MIL-STD-785), Maintainability Analysis

(MIL-STD-471), System Safety and Hazard Analysis (55HA, MIL-STD-882), and Failure Modes, Effects and Criticality Analysis (FMECA, MIL-STD-1629). These analyses are updated based on accelerated life test data. Combined with prior experience on similar engines, the ENSIP data base is used to define the initial preventive maintenance program. Early feedback on engine failure distributions and modes is provided by inspection programs and service reports (SRs) on operational problems. Changes in preventive maintenance and design are made with safety as the priority (38:viii).

After several years, the data base accumulates and begins to stabilize. More consistent reliability properties emerge for the engine parts, enabling a more statistical approach to analysis.

<u>Actuarial Analysis</u>

Nowlan and Heap (24:453) define actuarial analysis as 'statistical analysis of failure data to determine the age-reliability characteristics of an item'. Its primary use is to establish overall age limits for complex systems. This is useful only where a large proportion survive to an age at which the conditional probability of failure (i.e. failure rate), increases rapidly. An age limit is usually determined by plotting failure ages in frequency distributions, based on maintenance data or a large number of life tests. These enable an approximation to the conditional

probability of failure and probability of survival to a given age. Based on this, an age limit can be set, to remove the item when it is degraded but before it fails completely.

Actuarial analysis has significant limitations, some of them described by Nowlan and Heap (24:390-419). Age-reliability relations are altered by unfailed parts and mixed design configurations. Actuarial analysis for smaller components usually involves special data collection which is expensive. Nowlan and Heap also mention that changing design and usage of a system may cause a mix of age-reliability properties over the time span of data collection (24:395). In the case of serious, costly failures, collecting a sample of adequate size if often undesirable (24:391). For other components, an age limit may not be cost effective.

Nevertheless, actuarial analysis is extensively used for Air Force engines. For the F100 engine, it is used to track removal ages for the F100 engine and each of its modules, as described in AFM 400-1, volume II. Removal ages and reasons are tracked in the D042 Comprehensive Engine Management System (CEMS). Removal ages are graphed in frequency distributions for 200 hour age intervals, like that shown in figure 2(b), and are used to estimate actuarial engine life (AEL). This is data reviewed annually by

the Engine Life Planning Board (ELPB) to set maximum operating hour (MOH) limits for F100 engines and modules. MOH determination is based on judgement, considering safety, readiness, cost, inventory, and other logistic objectives (18).

Age Exploration

Age exploration is defined in MIL-HDBK-266 as "the process of collecting and analyzing information from in-service equipment to determine the reliability characteristics of each item under actual operating conditions" (26:5). This is described by Nowlan and Heap as consisting of two activities (1) detection of reliability degradation and new failure modes, and (2) special data collection to evaluate applicability and effectiveness of maintenance tasks (24:23). Applicability of a task depends on failure properties of the item. Age limits are applicable where the failure rate increases with age. Effectiveness of a preventive maintenance task is evaluated in terms of the failure consequences (i.e. costs) which it prevents (24:36). These consequences are most often distinguished as safety, operational, and economic (3).

Nowlan and Heap describe actuarial analysis as one technique often used to determine age-reliability relationships (24:390-5). Figure 2(b) shows one way they suggest of plotting failure mode conditional probabilities

(24:125). Increasing failure rate (IFR) modes can be remedied by design changes or replacement of the component in a state of potential failure (reduced failure resistance) before it has failed functionally (24:31).

This approach may be impractical where the part has a long life relative to the system, and is made more difficult by continued design changes which may invalidate previous data (32:56). Resnikoff notes that for such cases, age-reliability properties must be estimated from relevant experience, design analysis, and accelerated testing. The Air Force has used programs such as Lead the Fleet (LTF) and accelerated mission testing (AMT) to accelerate the process of age-reliability exploration for engines (19:2). For the F100, this program is designated 'Pacer Century'.

The other age exploration activity is determining task cost-effectiveness. One typical method is to plot a measure of component support cost versus the length T of the inspection/test or replacement interval (24:395). The cost relationship could be estimated and a minimum identified - given enough points on the curve, gathered at the same time. The variation of interval lengths which is necessary to do this involves costs of holding several different policies at once or changing them. Data may be invalidated by design or usage changes. These factors are

in addition to uncertainties which may already exist in cost data and measurement of engine operating time rather then actual component age. Figure 3 illustrates how given these uncertainties and a sparse plot, the cost-interval relationship is far from certain.

C(T) is the sum of failure, repair, and preventive replacement costs. This indicates C(T) will be dependent on reliability, safety risk, and repair cost distributions and will rarely be first order continuous. Thus, the C(T) - T plot is only a projection of the actual cost relationship, which cannot reliably show extrema, or prove continuity.

Although actuarial-type plots of task cost-effectiveness are of questionable value, the C(T) - T relation can in some cases be approximated as a continuous distribution related to the item reliability function and known cost parameters. Barlow and Proschan provide an example of this for minimizing long run total cost (3:91-95).

Reliability Centered Maintenance (RCM)

The Air Force RCM program is described in regulation AFLC/AFSC 66-35. It defines the objective of RCM as to make sure the equipment is in good working condition through prescription of scheduled maintenance only as required to preserve safety and reliability of the system. The RCM program defines preventive maintenance requirements

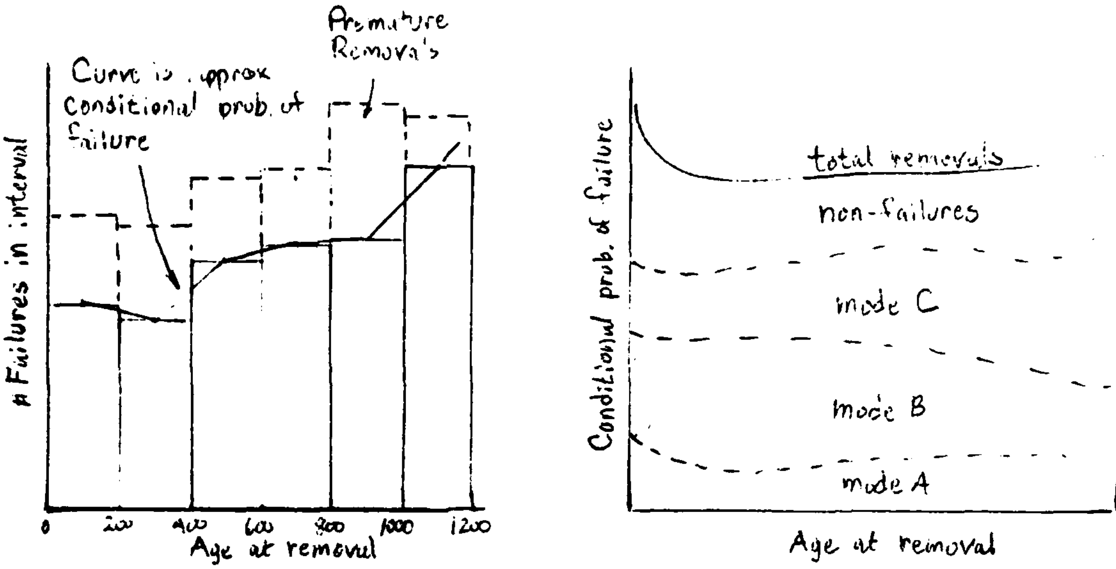


Figure 2: Actuarial analysis (a) Frequency distribution of ages at failure, and (b) partition of failure probabilities by mode

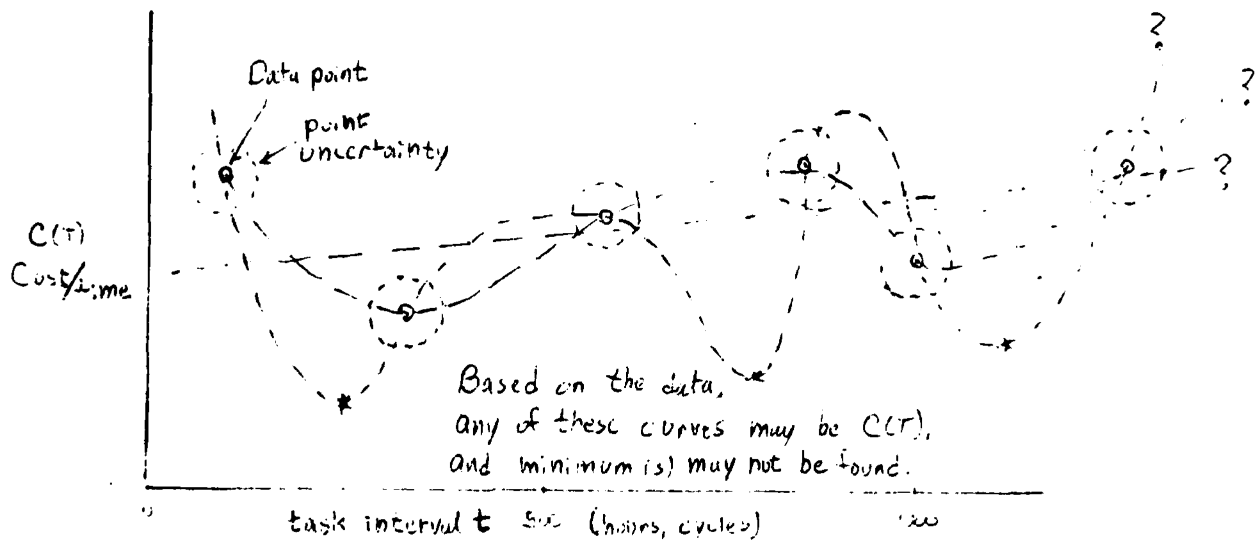


Figure 3: Uncertainties in the use of age exploration to find minimum cost intervals.

as part of the overall maintenance plan analysis, which, in turn, is a subelement of Logistic Support Analysis (LSA, MIL-STD-1388), in support of the Integrated Logistic Support (ILS) program. RCM includes a Failure Modes, Effects and Criticality Analysis (FMECA, MIL-STD-1629), a decision logic process to select components, selection of maintenance strategy and specific tasks for the system and an interval analysis (15:2).

RCM analysis procedures are described in MIL-R-5096D, Inspection System Requirements, where the RCM objective is stated as being, "to prevent the deterioration of the inherent levels of reliability and operating safety of the equipment (25:1)." MIL-R-5096D lists the following six steps for the analysis of turbine engines (25:1):

1. Maintenance Significant Items (MSIs) are identified, and functionally described. This generally includes several hundred items for an engine, at levels of module/system, assembly/line replaceable unit (LRU), and shop replaceable units (SRU).

2. Items and failure modes having safety impacts are identified in a Subsystem Safety and Hazard Analysis (SSHA).

3. The FMECA is performed to identify failure modes, effects, symptoms, consequences and means of detection.

4. As part of the FMECA, a criticality ranking is computed for each MSI. It is based on failure mode consequences, failure mode proportions in the item failure, and criticality of the item's failure.

5. Applicable tasks and their effectiveness are determined, using RCM decision logic.

6. Task intervals are identified by setting default intervals, which are gradually extended based on age exploration.

The first four steps are usually accomplished in the FMECA. The RCM decision logic presently used in MIL-R-5096D is shown in Figure 4. It is based on the logic structure published by the second FAA/airline maintenance steering group (MSG-2) in 1970 (22). Three questions must be answered for each failure mode:

1. Is a reduction in failure resistance detectable by routine monitoring of the flight crew?

2. Is a reduction in failure resistance detectable by on site maintenance crews or unit testing?

3. Does the failure mode have a direct adverse safety effect?

The fourth question asks if the item function is hidden, and the fifth if there is an adverse relationship between age and reliability, i.e. increasing failure rate

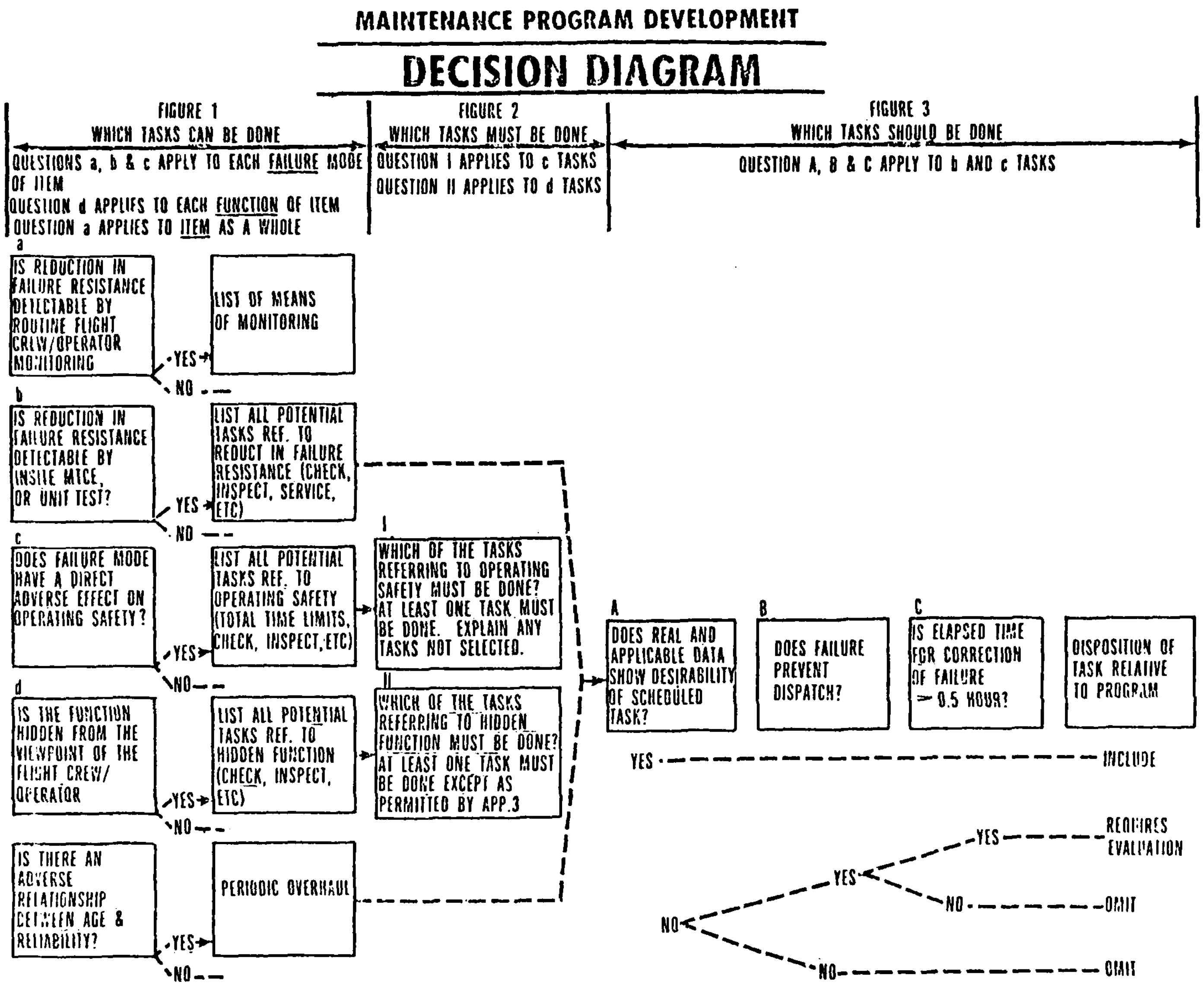


Fig 4. MSG-2 Decision Logic used in Air Force RCM (26:15)

(IFR).

These questions lead to selection of one or more tasks from the applicable tasks which are identified, and the most cost effective option is selected. The general task types which are possible include on-condition (inspection), rework (overhaul) or discard at some interval, incpection for a hidden failure, redesign, or no task at all (condition-monitoring). A revised decision logic issued as MSG-3 includes essentially the same questions, but leads from failure consequences to tasks (23).

Task interval determination is a necessary part of the RCM plan, but is not included in the decision logic (15:7). AFLC/AFSCR 66-35 and MIL-R-5096D describe interval determination only in general terms, as a process of setting initial conservative intervals which are gradually expanded through an age exploration process.

The F100 RCM analysis (12) considered more than six hundred components at engine, module/system, assembly, LRU, and SRU level. Preventive maintenance requirements were established for approximately 250 items, including seventy with replacement limits stated in terms of maximum operating hours (MOH) or low cycle fatigue (LCF) cycles (function of start/stop and turbine temperature cycles).

The stated objective of the requirements so defined is to result in a scheduled maintenance plan (SMP) of

maintenance tasks resulting in "minimum maintenance costs without adversely impacting safety, readiness, or reliability" [12.2:1].

The analysis procedures include this description of interval determination:

> The inspection interval for effective on-condition and hard time tasks is developed using field data, when sufficient, to provide clear definition of failure rates. Task intervals so determined are placed at the nearest existing aircraft-related interval whenever possible so as not to impose engine-peculiar inspection intervals. [12.2].

The F100 RCM analysis report contains interval recommendation changes to the existing preventive maintenance program.

The Air Force RCM program has emphasized definition of on-aircraft preventive maintenance requirements, primarily for LRU-level components. However, engines present a quite different analysis problem since there are five levels of parts and three repair levels at which preventive maintenance may occur. This results in optimal preventive maintenance requirements which are more interdependent with engine and module removal patterns and level of repair analysis.

The implementation of RCM for the F100 requires detailed failure information. Integration of the numerous data sources into one engine data bank is one objective of

the D042 Comprehensive Engine Management System (CEMS) (27:2). A basic problem in data collection is that the component age is not usually the same as operating hours on the engine (32:18).

As for quantitative evaluation of RCM benefits only one study was found. Singpurwalla and Talbott reported on maintenance data for the C-141 before and after RCM implementation. They state:

> "Although management had expected a decrease in scheduled maintenance activity (with no change in unscheduled maintenance activity) and an increase in availability, there is no evidence of any such RCM benefits." [32:15]

<u>Cost Modeling</u>

Several computer simulation models have been developed to investigate the economics of allowing a range of replacement times around a set age limit, known as opportunistic replacement. These include models of F100 engine module replacement by Forbes and Wyatt in 1976 (9) and Duval and Goetz in 1978 (8). Madden and Williamson (21) developed a multi-level monte-carlo simulation known as Operations and Maintenance Engine Simulator (OMEMS). This model is in use by Air Force Logistics Command (AFLC) to forecast repair demands and costs for life limited (age-replacement) parts in a mature engine. All three of these models used long-run average dollar cost as the objective. Each one was used to optimize the allowable range of

removal times (window) around the age replacement limit, but did not address optimization of the basic age limit for the module or part.

Problem

Current actuarial methods of interval determination bear no direct relationship to a management objective, i.e. minimum cost or maximum availability. On the other hand, age exploration can take considerable time and may not produce optimal answers. Ineffective interval determination is especially costly in the case of parts replacement. This may be a significant factor in the absence of verifiable RCM benefits. Bergmann (6) has proposed a graphic interval determination technique, but it has not been used or studied for Air Force jet engines.

Research Objectives

The objective of this research project is to demonstrate a procedure, practical considerations, and potential benefits of an interval determination technique for the F100 engine. This leads to three basic research questions:

1. What is a practical method for interval determination which can use existing information?

2. What practical considerations are involved in use of this method?

3. What cost reductions or readiness improvement

would be expected for each component?

Research Strategy

The Bergmann graphic technique enables determination of optimum replacement intervals, for simple two-state, independent components. These assumptions are reasonable for many engine accessories and small parts. The primary data requirements are for age-at-failure records and data to establish costs of failure and preventive replacement. Several F100 components were chosen to provide a case study. The age-at-failure data, failure modes, and narrative for many failures are available from the F100 SR data file. The data can be directly used in the Bergmann technique, and also characterized by failure distribution as a cross-check. Costs of failure and replacement can be estimated based on part cost, the SR failure records, and safety, availability, and maintenance events accountable to the component. The basic value of the graphic method could be assessed by comparing the results for different objectives, failure distributions, and costs. A case study is used to illustrate a practical usable procedure for determining replacement intervals, in addition to showing its potential value as a standard analysis tool.

Sequence of Presentation

The remainder of this report includes a review of

literature in chapter two, description of the methodology in chapter three, summary of data collection, analysis, and results in chapter four, and conclusions and recommendations in chapter five. The recommendations include replacement intervals for each of the components, potential use of the graphic method, and areas which may be worth further study.

CHAPTER II

LITERATURE REVIEW

A maintenance strategy is a set of control actions (tasks and decision rule) which are performed to restore the performance of a system (11:24-25). This chapter summarizes some major ideas in preventive maintenance strategies, their use in engines, and specific topics to support the methodology.

Preventive Maintenance Strategies

Simple-system and complex-system models represent two basic perspectives on preventive maintenance strategy. The simple system perspective assumes component failure properties and interrelationships (if any) can be defined if not fully known (28:56). In contrast, the complex system perspective views the system as a diverse set of components in many intermediate states and relations, which cannot be individually known (28:56-57). The simple system involves definable state changes described in terms of failure and renewal, whereas the complex system state is not determinate.

Simple System Strategies

The basic case of a simple system is that of a single, independent element which is either good or failed. Talbott (33:1-2) describes four possible strategy options

for this system, based on two kinds of information - age and condition. The first is age replacement, the replacement or repair of the component to new condition at failure or some age limit T, whichever occurs first. The failure (condition) must be evident, hence both age and condition information are required. The second strategy is block replacement, where all components of a population are replaced at failure for fixed intervals of T, regardless of age. Failure must be evident, but it is not necessary to track age. The only uncertainty for these replacement strategies is the item's life. If the item's condition is unknown except by inspection, then both the item's life and condition are unknown. A third strategy, for these circumstances, is periodic inspection at every interval T units of age, with replacement of failures which are discovered. The fourth strategy is blind replacement, replacement every T units of time without inspection. This is useful only if the item condition is unknown and the cost of replacement is less than the cost of inspection.

Barlow and Proschan (2) describe two other significant simple system strategies. The first is periodic inspection to minimize the cost until failure detection (2:108-10). This might also be referred to as condition monitoring. Failure is known only through the inspection/test, and the testing does not affect the system. Each

check incurs a fixed cost, and time elapsed between system failure and the next check (or a 'miss') incurs some greater fixed cost. The second strategy is opportunistic replacement, of one part in a group of condition-monitored components (2:117-18). The parts are assumed to be in series and have independent failure distributions. The state of the monitored part A is known, but state of the opportunistically replaced part B is not known. Dynamic programming can be used to define a policy (n,N) with three possible actions: a) if part A fails with the age of part B between 0 and n, replace part A only; b) if part A fails when part B is between age n and N, replace both parts A and B; and c) if part A has not yet failed when the age of part B is N, replace only part B.

These are commonly seen simple-system strategies used for lower level components such as engine LRUs.

<u>Complex System Strategies</u>

A macro level perspective on complex system maintenance is described by Resnikoff (28). He deals with the case where components' failure properties, states, and relations cannot be described or idealized practically (28:57). The set of strategies to be used is determined in three steps. These are (1) The system is partitioned into maximally independent sets with respect to failure consequences; (2) expressions are developed for the costs

of maintenance and consequences of failure, and (3) the total support cost function is minimized iteratively by repeated selection of a policy option which offers the greatest marginal cost reduction (28:61). Resnikoff describes the principle options as redesign, maintenance management improvements which affect only costs, and usage/maintenance policy alterations which affect both total cost and failure properties of the component (28:71). This third group of options includes revision of task intervals.

This macro-approach to defining maintenance strategy can be geometrically described as seeking a local maximum rate of descent on a surface which represents total system cost (28:73). Such a concept is the theoretical basis claimed for Reliability Centered Maintenance (28: 59-74).

The RCM approach is thus one of incremental optimization. In theory, it requires minimum information on component failure modes and distributions (28:58). But in practice, such information is needed anyway (32:19). First the incremental basis of RCM is of little help in establishing or re-evaluating the overall interval baselines in a maintenance program. Instead, default intervals are set (15:7). The Air Force regulation on RCM specifically excludes interval determination from the formal RCM analysis, the point at which applicability and cost effectiveness of

tasks is evaluated (15:7). However, as mentioned previously, evaluation of task applicability and effectiveness requires age-at-failure and cost data in some form. This is data of the same type needed to evaluate simple system strategies as well.

The RCM approach emphasizes a complex system strategy thereby excluding task interval as a specific variable. Conversely, the simple system approach could center on determination of the interval for a specific strategy.

F100 Maintenance Strategies

F100 maintenance strategies are prescribed in work packages for scheduled, unscheduled, and conditional maintenance, for both base level and depot. These establish inspection and test requirements for the engine, modules, LRUs, and lower level parts.

The strategies used include each of those described for simple systems, except blind replacement. There are also conditional tasks required upon occurrence of some event. The engine has no age limit (MOT) as a whole. However, three of the modules have age limits. Thirty two lower-level parts are time-limited, and another fifty-six structural and rotating parts have LCF limits. These 'life limits' are a form of age replacement. The 2J-F100-6 engine intermediate maintenance manual also defines some

opportunistic replacement requirements for less accessible engine parts, and other conditional replacements, to be done upon occurrence of certain engine problems or events.

There are also inspection/test requirements, which include strategies of condition monitoring, block replacement, periodic inspection, opportunistic inspection, and conditional inspection. Condition monitoring for the F100 includes both crew observation of engine and aircraft fault indications, and routine pre/post/thru flight inspections listed in the 1F-15-6 and 1F-16-6 technical orders (T.O.s) which list scheduled maintenance requirements. These routine checks include inspections of engine inlet, generator connectors, and taking oil samples. Periodic inspection requirements are also listed in the aircraft -6 T.O.s. These include 'periodic' inspections of specific parts at intervals of 100 to 1500 hours, and phase inspections at 1000 to 4000 hours. During phase inspection, the engine and aircraft are disassembled and inspected where prescribed, with parts replaced if failed (i.e. out of condition limits). This corresponds to a block replacement strategy. The aircraft -6 T.O. also contains another section listing special inspection requirements. These include opportunistic inspections where other maintenance provides access, and conditional inspections required upon occurrence of some engine problem or maintenance action. For example,

there are forty inspection tasks required at every engine removel. Other similar requirements are given in the engine depot maintenance (2J-F100-3), intermediate maintenance (2J-F100-6), conditional maintenance (2J-F100-26-2) and repair work package (2J-F100-WP-XX) technical manuals.

As mentioned in Chapter 1, many of these requirements were affected by RCM analysis. However, its scope is limited to scheduled preventive maintenance. This includes primarily the age replacement, block replacement, periodic inspection requirements, and condition monitoring inspections. Age replacement is used for the parts whose failure is most critical, hence it was chosen as the focus of this case study. Limitations of time and size of this project precluded a study of interval determination techniques for the block replacement or periodic inspection models, the only others defined using a task interval.

Age Replacement Model

A general form of the age replacement model for a simple, two-state system is given by Barlow and Proschan for a single, independent component which is either good or failed (2:85-94). They describe a strategy of repair or replace to new condition at age T or failure, whichever occurs first, with an objective of minimum long run cost. The failure distribution $F(T)$ and its complement $\bar{F}(T)$ are assumed to be continuous and known with certainty. The

expected costs C_1 of failure and C_2 of preventive replacement are also known. A repair cycle is completed every time that a failure/repair or age replacement occurs. The cost per operating hour is the ratio of expected cost per cycle to expected length of the cycle. This can be stated as

$$C(T) = \frac{C_1\ F(T) + C_2\ \bar{F}(T)}{\int_0^T \bar{F}(t)dt} = \frac{\text{expected cost}}{\text{expected cycle length}}$$

Barlow and Proschan show that the optimum interval T^* occurs when the deriviative of this expression is zero, therefore

$$\frac{f(T^*)}{\bar{F}(T^*)} = \int_0^t \bar{F}(t)dt - F(T^*) = \frac{C_2}{C_1 - C_2}$$

where $\frac{f(T)}{\bar{F}(T)}$ is the failure rate. This will exist when $C_2 < C_1$ and when F is an increasing failure rate (IFR) distribution (2:87). This model is usable for whatever cost objectives are chosen.

Bergmann (6) describes a technique of determining the age replacement interval T^* by using a total time on test (TTT) plot. Given data on n independent ages at failure, $(X_1, X_2 \ldots X_n)$, the total time on test through the ith failure time T_i (X_i) can be calculated from

$$T_i(X_i) = \sum_{i=1}^{n} (n-i+1)(X_i - X_{i-1})$$

where j is the moving index. Table 1 shows an example of calculations for a TTT plot. The ratio $U_i = \frac{T_i(X_i)}{T_n(X)}$ is the proportion of samples' total time on test through the ith failure for a sample of size N. This is plotted versus i/N to create the TTT plot. The 45^0 line is characteristic of an exponential failure distribution. A concave plot indicates an IFR failure distribution, and a convex plot indicates a decreasing failure rate (DFR) distribution.

Bergmann shows how the optimal interval T* can be determined by constructing a tangent to the TTT plot from the point $-\frac{C_2}{C_1-C_2}$ on the horizontal plot axis. The value of U* and i/N* at the tangent point corresponds with a value T* in the sample. This is the point where $U_i=\frac{T_i(X_i)}{T_n(X)}$ is as large as possible and C + i/n is as small as possible. Thus relative costs can be compared using the ratio $(C+i/n)/U_i$, cost per unit operating time. Figure 7 shows interval determination for the plot of figure 6, using cost values of C_1=\$20, C_2=\$10, and $\frac{C_2}{C_1-C_2} = 1.0$. The ratio $\frac{C_2}{C_1-C_2}$ represents a standard cost, which is non-dimensional. Hence, costs can be expressed in dollars, down time, or whatever combination is appropriate (3:85).

This graphic technique does have practical

TABLE I

Calculations For a Total Time on Test (TTT) Plot

Ani	Age t	$(n-i+1)$	$T_{i-1} + (t_i - t_{i-1})(n-i+1)$	$= T_i$	i/N	$U = T_i/T_n$
1	4	5	0 + (4x5)	= 20	.20	.168
2	15	4	20 + (11x4)	= 64	.40	.538
3	25	3	64 + (10x3)	= 94	.60	.790
4	35	2	94 + (10x2)	=114	.80	.958
5	40	1	114 + (5x1)	=119	1.00	1.00
n=5				T_j=119		

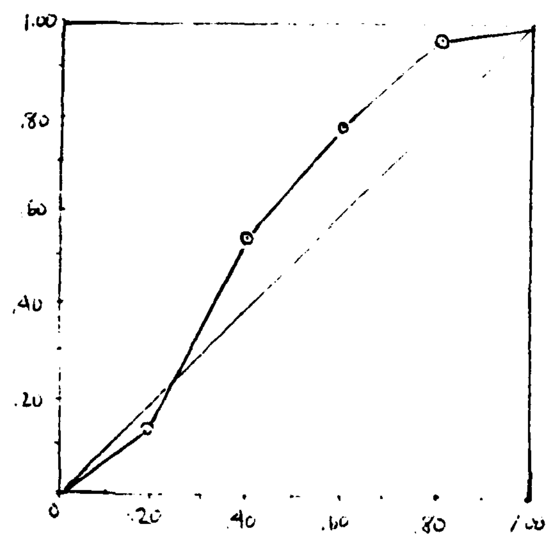


Figure 5: TTT plot for calculations in Table 1

C = .50

U* = .96

i/N* = .80

T* = 114 hours

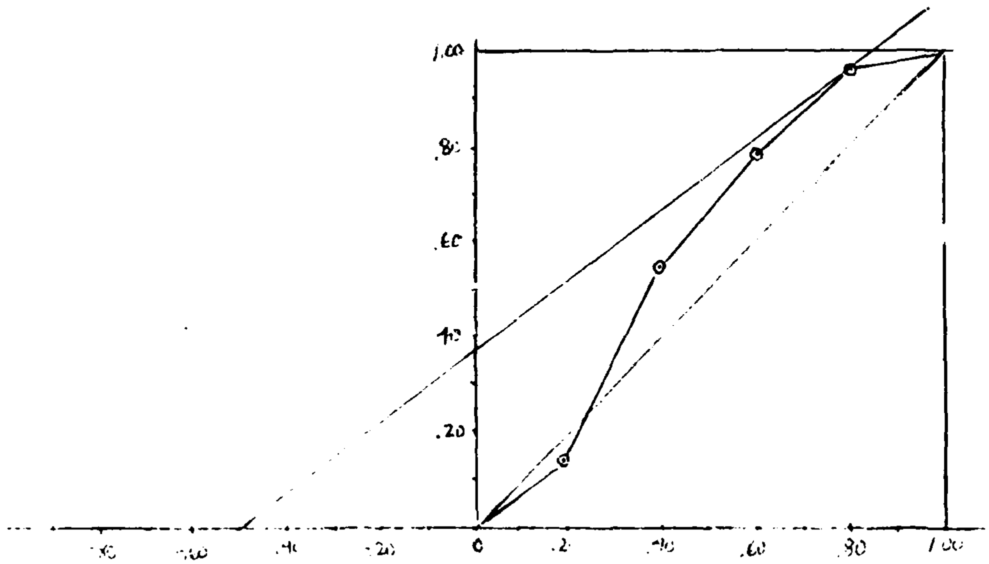
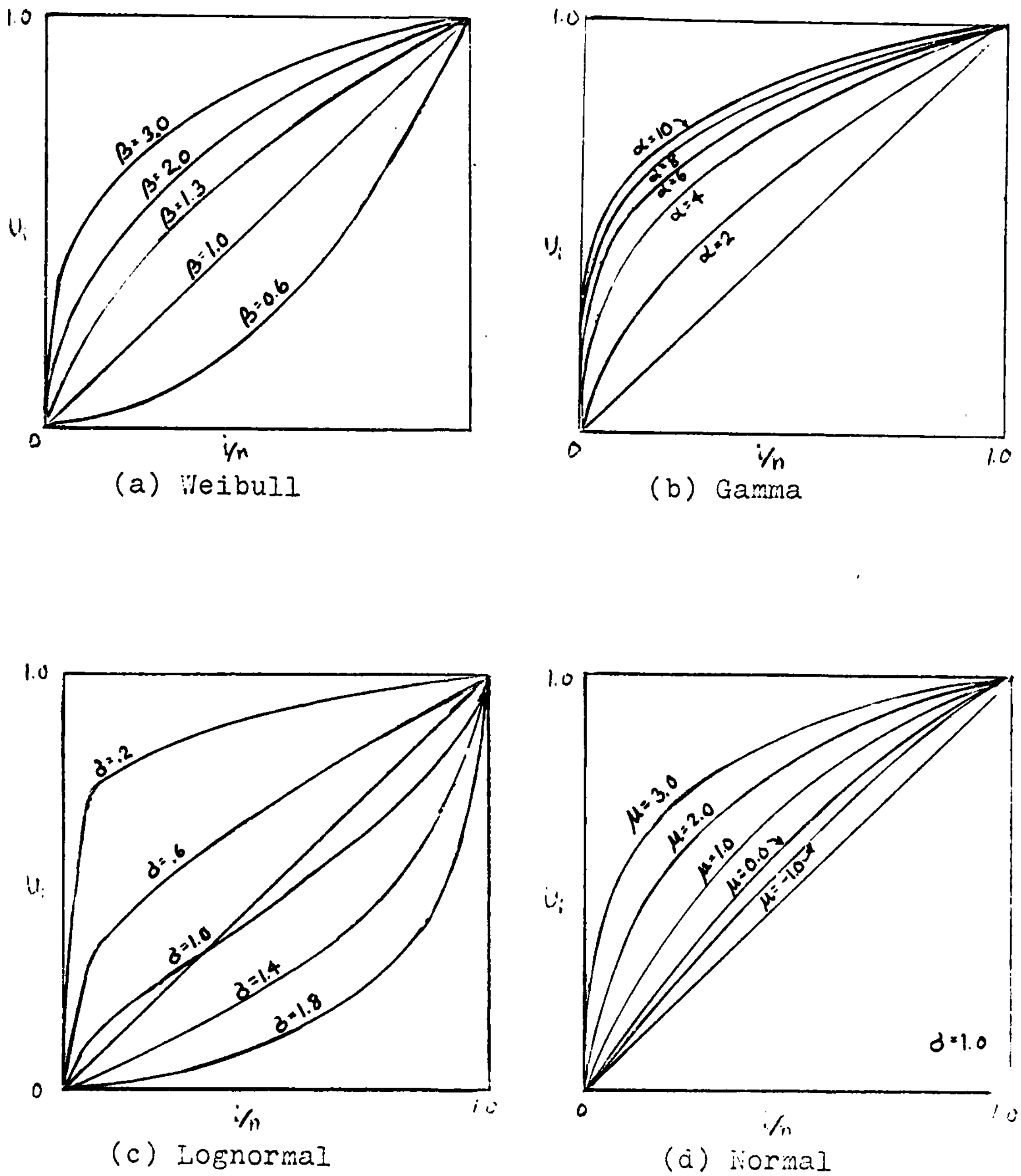


Figure 6: Example of TTT Plot Interval Determination

limitations in how well it models the actual component. When actual data is used, sample size, removals of unfailed parts early (withdrawals), and truncation by removal at an age limit can seriously affect the result.

Barlow and Proschan (2) discuss methods of analyzing incomplete data which can be applied in empirical use of TTT plots. As the sample size increases, the underlying failure distribution converges to that of the population (2:451). Figure 7 shows TTT transforms of four basic reliability distributions for a range of parameter values. The sensitivity of TTT plots in reflecting the underlying failure distribution is useful in the case of truncated data. Barlow and Proschan suggest that for a sample of size n truncated at item m, a TTT plot of $U_i = \frac{T_i(X)}{T_m(X)}$ versus i/m will indicate the underlying distribution.

Barlow and Proschan describe tests which can be used to aid in identifying the failure distribution from truncated (censored) data. The presence of an exponential distribution can be discerned by a 'crossing' test (2:465). If F is exponential and n is the number of failures, the probability of the TTT plot lying entirely above the 45° line or entirely below the 45° line is 1/n. Based on this, probabilities of crossings above and below in the TTT plot can be estimated. The presence of an IFR model can be



(a) Weibull (b) Gamma

(c) Lognormal (d) Normal

Figure 7: Scaled Total Time on Test Transforms 2:456

confirmed where the TTT plot lies completely above the 45° line, at a confidence level of i/n (2:469). The DFR distribution is present when the converse occurs. Another suggested test for IFR and DFR is total area between the TTT plot and the 45° line, compared against a tabulated statistic (2:470). Barlow and Proschan show that the scaled TTT plot from a truncated sample will always stochastically dominate (be farther from exponential) than plots of the same sample size from complete data. Figure 8 shows an example comparison given by Barlow and Proschan (2:472).

Another case is that of withdrawals, where some components are removed before failure at various ages. Barlow and Proschan suggest piecewise linear approximation of failure rates over incensored intervals (3:473).

Another consideration is of TTT plots from two samples. This may be useful in comparing results from actual data versus an estimated distribution, comparing one year to the next for a component, or testing age samples from two different operating locations. Barlow and Proschan note that for a control group of size n and sample group of size m, the probability is i/n that the TTT plot of either will lie completely above the other, given the distributions are equal and continuous (2:475).

The cases of truncation or withdrawals in the data can also be dealt with by graphic estimation of an

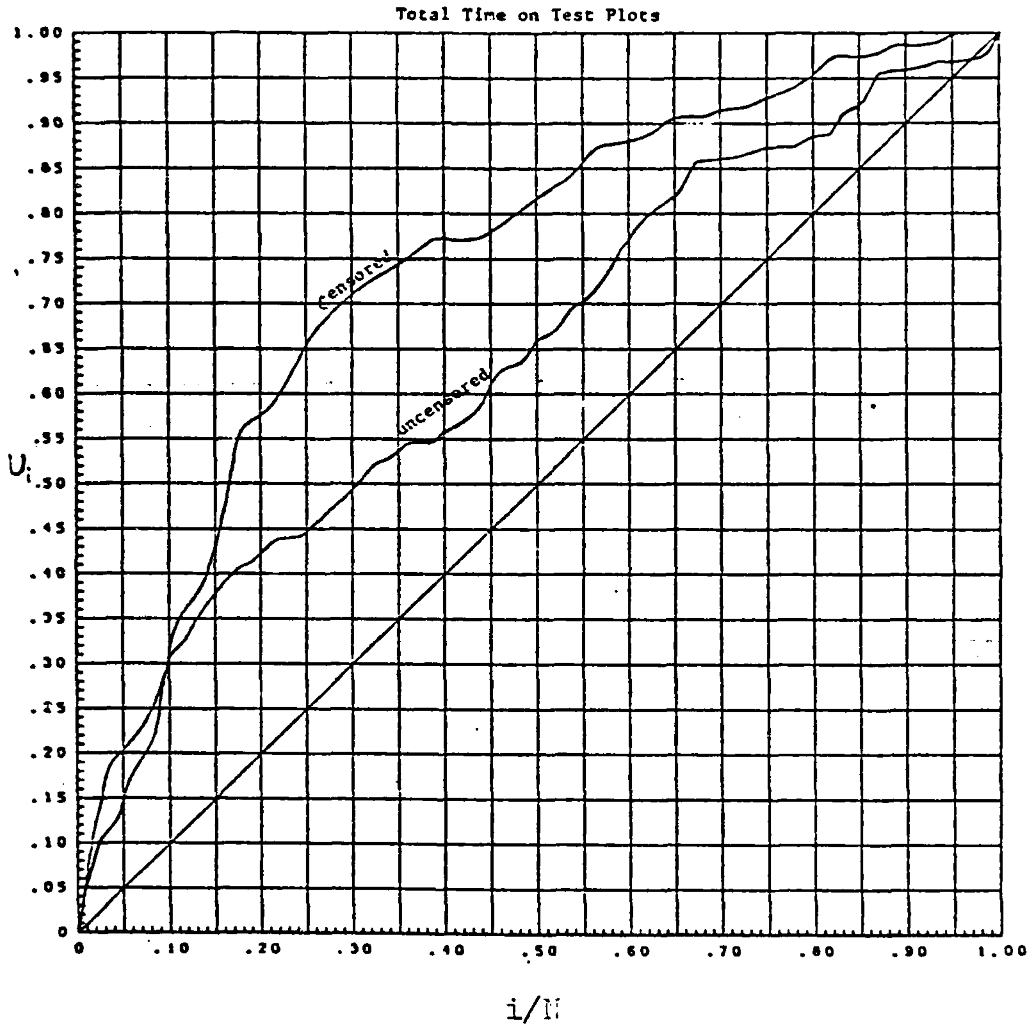


Figure 8: Comparison of TTT plots for simulated Weibull data, β=1.5 from Barlow and Proschan (2:472)

underlying distribution, and plotting of the TTT transform for the full sample size. Barlow and Proschan provide a review of failure processes, and the Weibull, normal, lognormal, and gamma distributions (3:9-44). Kao provides a summary-plotting and interpretation techniques for each of these distributions (20:12-17).

While the model here considers the simple component as having one failure distribution, it really is a composite of failure mode distributions. Bazovsky discusses chance and wearout/aging, emphasizing the relation of component strength and stress levels (5:53-95).

The basic tests to check the curve fits are the Kolmogorov-Smirnov test, based on maximum deviation of a sample point from the curve fit, and the chi-square test, based on the sum of squared deviations of data from the curve fit. Another tool which also uses the sum-of-squared deviations is the F test. It can be used in two sample tests, for example, to find if differences due to design change or operating location are significant based on sum-squared deviations. Each of these techniques is reviewed by Amstadter (1:50-90). He suggests that a minimum of 10 failures are needed to estimate a Weibull distribution without prior information.

Costs and Effectiveness

The age replacement model requires information to establish the per-event costs C_1 of failure and C_2 of replacement, and to measure the objective C(T). As used in the Bergmann graphic model, the cost is a ratio $C = \frac{C_2}{C_1 - C_2}$ which is non dimensional. Thus, selection of cost measures need only be appropriate to the objective.

Preventive Maintenance Theory

Two basic perspectives appear most often in literature on models of preventive maintenance - use of dollar cost or availability as cost measures. Barlow and Proschan suggest dollars, time, or some combination for use as costs (3:84-85). Models may also differ in the time horizon used, i.e. infinite (long run) or finite (short run). Talbott describes a Radner Jorgenson blind replacement model, which expresses costs in down time and the objective as observed availability, ratio of uptime to total time over the renewal cycle (33:13). Gertsbakh describes models which minimize dollar cost or maximize availability (11:9-11).

RCM Methods

Literature on Reliability Centered Maintenance is vague on this matter. The Air Force Regulation does not direct how objectives or costs will be measured, but says in use of the decision logic 'Avoid considerations that

would compromise safety, reliability, or economy' (26:7). There are no criteria specified for this purpose. MIL-5096D provides instructions for use of the RCM decision logic, and describes preservation of inherent reliability as the program objective (25:1). Selection of the tasks which must be done because of safety operational or economic value is based on yes/no answers to decision logic questions, but no measures of safety/operational or economic value of a task are proposed. In one statement, premature removal rate is given as an example of a reliability measure.

The Navy MIL-HDBK-266 on RCM analysis suggests a specific procedure for selecting cost-effective RCM tasks, based on long-run applicability and effectiveness. Applicability is determined (yes/no) based on the item failure age distribution, and some age where conditional probability of failure shows a rapid increase (26:36). Task effectivness is measured by its prevention of failure consequences, identified as safety, hidden, operational, and economic. For safety consequences, the measure used is an acceptable risk of critical failure. For hidden failures, the MTBF of multiple failure is used as a measure.

For operational and economic consequences, the Navy handbook suggests use of cost-benefit ratios (CBRs). For purely economic consequences, costs of preventive

maintenance C_{pm} and corrective maintenance C_{cm} are computed based on labor:

$$C_{pm} = (\#\text{times/year})(\text{manhours/task})(\text{labor cost/hour})$$

$$C_{cm} = (\#\text{failures prevented})(\text{manhours/task})(\text{labor cost/hour})$$

If the ratio $CBR = \frac{C_{pm}}{C_{cm}}$ is less than one, the task is considered cost-effective. For operational consequences, the cost of failure is the sum of costs of lost operational time C_{op} and costs of corrective maintenance C_{cm}, where

$$C_{op} = (\#\text{hours lost/failure})(\#\text{failures})\left(\frac{\text{acquisition cost}}{\text{life cycle op hours}}\right)$$

and $C_{opc} = C_{op} + C_{cm}$

The cost benefit ratio is then $CBR = \frac{C_{pm}}{C_{opc}}$ and the task is considered effective when the ratio is less than one (26:40-42).

Several aspects of the MIL-HDBK-266 approach have implicit assumptions. First is an underlying assumption that failure distributions are exponential (constant failure rate) implied by use of the word 'failure rate' rather than failure distribution. However, the justification for most tasks, particularly age replacement, is to prevent consequences of items and failure modes whose failure rates increase with age. Without knowledge of component failure mode age distributions and their consequence

distributions, estimation of 'failures prevented' may be difficult. Secondly, the handbook's expressions for costs of corrective and preventive maintenance are based only on labor hours, so there also is an implicit assumption that material, engine life, or other costs are not significant.

Reliability and Effectiveness Literature

Costs of preventive and corrective maintenance are also discussed in reliability and system design literature. Seiler (29:9-20) identifies the basic cost elements of concern here as material, labor, and capital, and further distinguishes costs as fixed/variable and short run/long run. The material costs include not only the part, but spares and power or fuel as well. For measuring the objective C(T), he identifies two primary options - a simple ratio model and an indifference curve model. Seiler distinguishes efficiency (maximum $\frac{\text{availability}}{\text{dollar cost}}$) and effectiveness (availability goal with constraints) as the two basic orientations in objective and cost measurement.

Welker (34:1-11) defines three criteria of effectiveness based on time measures. Intrinsic availability is the ratio of operating time to the sum of operating time and repair time. Availability (observed) is the ratio of operating time to the sum of operating and down time.

Operational readiness is the ratio of all good time to total calendar time.

Air Force Management

Engine failures, repair, and preventive maintenance costs are expressed in costs which reflect both the dollars and availability perspectives. The statistics typically compiled for the Engine Advisory Group (EAG) report include air abort rate, class A/B/C mishap rates, premature removal rate (PRR), or shop visit rate, SVR), percent of engines not mission capable (ENMC), maintenance labor hours per flight hour, inventory size, operating hours, dollar costs of depot and intermediate maintenance, and the dollar costs of fuel and spare engines and parts (37:250). These costs are sometimes expressed in terms of equivalent engines consumed (4:25). For engine components, an additional parameter of use is the not-repairable-this-station (NRTS) rate, the proportion of components sent for depot overhaul. To prioritize management attention, specific engine parts or systems are ranked in accountability for mishaps, aborts, unscheduled removals, and manhours (37:18).

Air Force Data Collection

Air Force data collection for engines is centered in the D042 (previously D024) Comprehensive Engine Management System (CEMS). This system currently provides records

on engine and module fleet status, removal ages and reasons for actuarial analysis, and tracking of accumulated time and LCF cycles on parts having age limits (27). The D042 currently does not provide age at removal or failure modes for engine components below module level. Studies of this data point out inherent uncertainties because engine time may not correspond to component age (32:18) and variation in usage and individual components across the fleet is considerable (35). Additional factors such as gaps in reporting or malfunctions of time/cycle recorders lead to additional uncertainty. Consequently, estimates of parts life lost by early removal are difficult. The D024/D042 CEMS engine data was studied by Green in 1981 (22). He noted that the reasons for removal recorded with engine removals are symptoms which correlate neither with failure modes or the maintenance actions reported in the maintenance data collection program. One of the objectives in the D024 update to D042 CEMS has been to correlate engine actions in D160, K051, D056, and D042 data collection programs and provide valid failure modes and effects records for components (43:1). However, several studies conclude that this possibility is limited by present acquisition of diagnostic information (32, 35).

Eventually, the CEMS is planned to interface with

other Air Force data systems to provide an integrated data base, adequate to track engine component failures, modes, and effects (27:1). These other data sources include the K051 system to provide component-accountable down time and events, the D056 and G098 systems which compile manhours, aborts and failures/actions; and the D160 component support cost system (CSCS) which provides dollar cost accounting. The CSCS accounts for direct and indirect material, labor, overhead, broken out by maintenance levels (16). Regulation AFR 400-31, Volume IV describes the specific algorithms and cost elements used. The basic classification used in allocating costs to components is a work unit code (WUC), which identifies the component and its level. For example, 23XXX indicates the engine, 23HXX indicates the fuel system for the F100, 23HAX indicates fuel flow control system, and 23 HAD identifies the main fuel pump.

The preceding review of engine maintenance strategy indicates that simple-system types of maintenance strategies correspond to the range of options used for engines and their parts. Selection is based on the complex system approach of RCM analysis, but unresponsive, inefficient methods of interval determination. Consequently, simple-system interval determination may complement the complex-system strategy selection of RCM analysis, by enabling credible,

responsive interval determination.

For the most costly strategy of age replacement, a simple graphic model and solution method can rapidly be used to determine intervals. This is a capability presently lacking in RCM. The graphic model requires age at failure data to develop a Total Time on Test (TTT) plot, and cost information to develop a standard cost value. A review of cost and effectiveness measures in use indicates that dollars and availability (down time, equipment lost) are two primary measures, and engine component costs can be expressed in those terms. The dominance of material costs for engines indicates that the labor basis of RCM cost-benefit analyses may be inappropriate in some cases.

CHAPTER III

METHODOLOGY

This chapter describes the components selected for this study and use of Bergmann's graphic method for determination of age replacement intervals. The emphasis is on use of existing information, a practical manual analysis method, and quick manual checks of the results. The method may then be useful in a low-skill, limited data peacetime or wartime environment.

F100 Engine Components

Five F100/F-15 components were chosen as the subjects for this study. The components which were selected are the main fuel pump, N2 (core speed) hydromechanical sensor, stator generator, convergent exhaust mozzle control (CENC), and the fuel oil cooler. Table 2 shows the maintenance data work unit code (WUC), part numbers, list price, and current age limit for each part.

These components each rank high in number of actions, labor and parts costs, and represent a manageable analysis problem. Each uses operating hours (not cycles) as the age parameter and has a distinct, relatively independent function. The failure of each component is evident (observable). Therefore, the basic requirements of the age replacement model are satisfied.

TABLE II

F100 Engine Component Description

COMPONENT	WORK UNIT CODE	PART NUMBER	AGE LIMIT	FUNCTION	LIST PRICE
Main Fuel Pump	23HAD	4054035 4038436	680	Fuel boost and main pressure for actuators, combustion	$34799
Convergent Exhaust	23PAB	4050640	750 900	Variable nozzle pneumatic pressure scheduling	$16995
Fuel Oil Cooler	23JAC	4048201 4044343	1250	Heat exchange - Fuel used to cool oil return	$ 8409
H2 Sensor,	23HAG	4041278 4056083	1000 1500	Control input signal	$ 3730
Stator Generator	23KAH	4044474 4048338	2000	Engine electric power for ignition, aux power	$ 3373

Figure 9 shows configuration of each component and its location on the engine. Each one is a line replaceable unit (LRU) accessible on the installed F-15 engine.

Main Fuel Pump

The main fuel pump supplies high pressure fuel to the Unified Control for the core engine, boost pressure fuel to the augmentor control, and continuous boost-pressure fuel for hydraulic actuators.

The fuel pump has been a troublesome component for maintenance. Over the period 1979-82, Air Force data shows 3600 unscheduled events, 397 confirmed failures, 30 aborts, approximately 19 related mishaps, and 24 related engine removals. The fuel pump on the average accounted for 1.14% of engine-accountable down time, plus inspections over 1979-1982. The consequences of failure range from high/low fuel flow to complete engine flameout.

The major design changes have included addition of servo fuel screens to prevent its internal jamming and contamination (1979), strengthening of the vane stage impeller (1982), shaft coupling (1982), and improved retention of an internal valve spring (1982).

N2 Hydromechanical Sensor

The N2 sensor transmits rotor speed of the high pressure compressor/turbine shaft. It is located on the

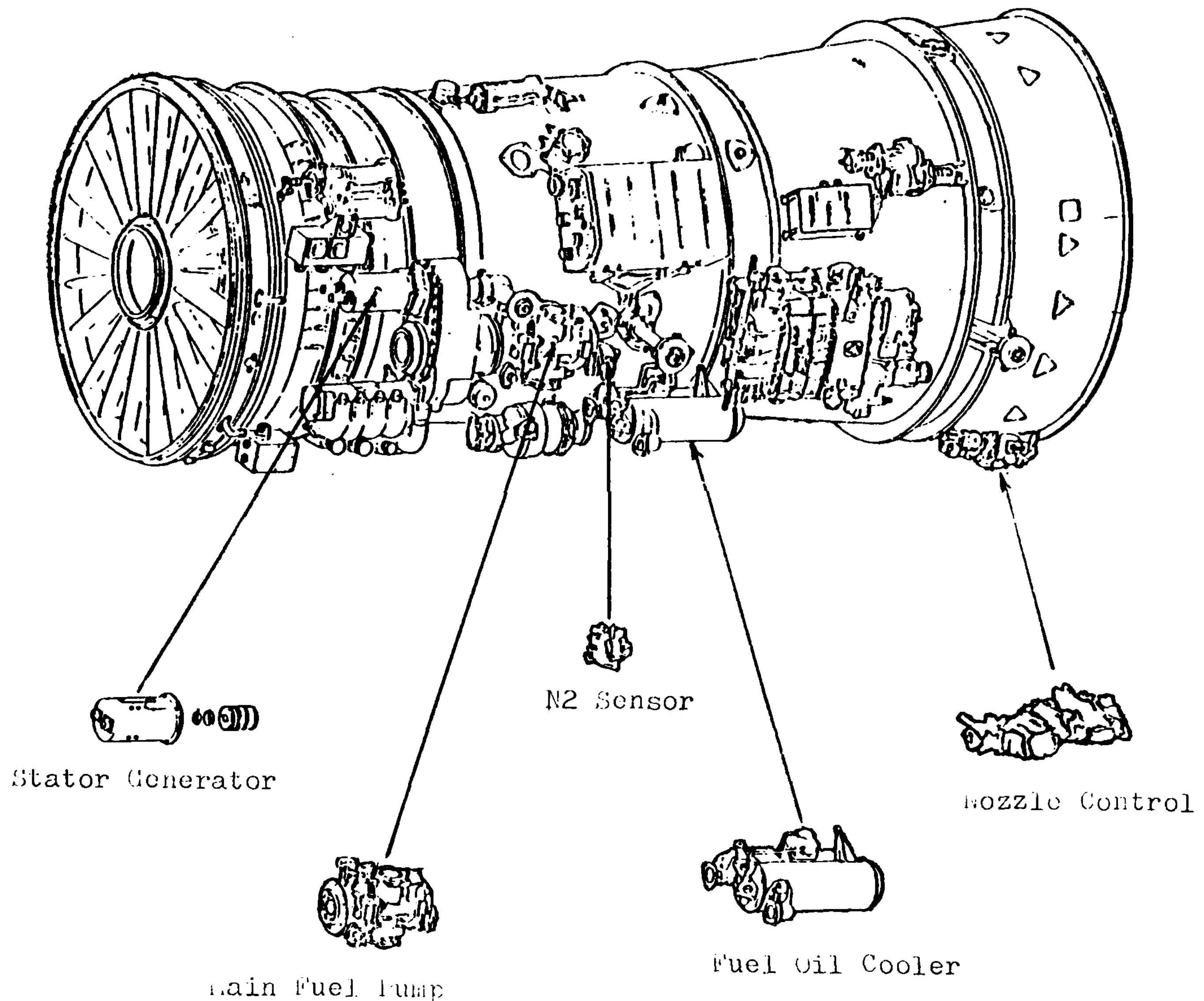


Figure 9: F100 engine components and location

main fuel pump to improve accessibility for the Unified Fuel Control (UFC).

The N2 sensor is one of the top 10 F100 parts causing aircraft aborts, accounting for about 3.5% of F100 caused aborts. During the period 1979-82, the N2 sensor was involved in 11 mishaps, 40 aborts, 2100 maintenance events, and had about 817 failures. When failed, the N2 sensor may cause fuel leakage, engine instability, or no throttle response. It provides a control signal input, so its maintenance often involves engine re-trim.

The principle design changes include a durability improvement (1979), followed by a new longer life design (1980).

Stator Generator

The generator consists of a stator and permanent magnetic rotor, mounted on the engine gearbox. It uses the engine gearbox bearing and shaft to provide an engine driven permanent magnet type power source. The generator provides power for ignition, spark, the electronic control (EEC) and control stepper motor and solenoid operation via the EEC.

The stator generator is another top cause of aborts, since shorts or loose connectors often cause instrument and power fluctuations and loss of airstart capability.

In the period 1979-82, the stator generator accounted for 6 mishaps, 45 aborts, 1770 maintenance events, and had 569 failures.

The main design changes have been improvements to the connectors (1979) and durability (1982).

Convergent Exhaust Nozzle Control (CENC)

The CENC positions the exhaust nozzle throat in response to area signals from the unified control (UFC).

The nozzle control is also a top 10 abort cause, accountable for 3.5% of F100-caused F-15 aborts. In the period 1979-82, the CENC caused 25 aborts, 2500 maintenance events, and had 569 reported failures. As part of the control system, its maintenance frequently involves engine trim and test runs.

The main design changes to the CENC include improved reliability (1979), improved piston stop (1979), and improved air motor bearing material (1981).

Fuel Oil Cooler

The Fuel Oil Cooler is a pressurized cylindrical heat exchanger unit. The fuel flow tends to warm the oil on ground starts, and cool it during operation at altitude, where ambiant temperature (and fuel tanks) remain cold.

The fuel oil cooler failure effects range from high or low oil pressure to internal leakage and mixing of

fuel with oil. Several burst failures occurred after failure of the augmentor pump controller and fuel over-pressure. Over the period 1979-82, the fuel oil cooler caused 8 aborts, 594 maintenance events, and had 169 reported failures.

Engine Information Sources

One objective in demonstrating the graphic method is to show how existing information may be used more effectively. Two basic types of information are required for the graphic technique. The first is information on component failure properties. Age at failure data is provided by the F100 Service Report (SR) system. This is a record file of component failure investigations used in engine development. The records usually identify location, conditions, failure mode(s), effects, and component age(s) related to the occurrence.

The ratio of failures to total removals can be determined from D056. This can be used as an estimate of the cumulative percent failed in service, assuming unfailed parts are removed at the present. The F100 SR data file contains only failures reported for development purpose, five to ten percent of those which have occurred. Component ages given are in engine total operating time (TOT), which may not match actualcomponent age. However,

the SR data file is the primary age-at-failure data which the Air Force has for these F100 components. The current age replacement intervals for each component are provided in T.O. 1F-15A-6.

Three Air Force data systems provide component maintenance data which can be used to compute costs. D056 provides records on aborts, maintenance events and manhours accounted to the components' work unit code. D051 provides aborts, down hours, and direct manhours accountable to components, and percentage of aircraft downtime for which the engine and component are accountable. D160B provides base level costs, direct and indirect, including labor, material, supplies, and transportation.

Method of Analysis

The graphic solution technique can be viewed as a three step process of data collection, transformation to parameters of the age replacement model, and determination of the optimum interval, illustrated in figure 10. If the sample is representative, ages at failure are available and costs are known, then the solution is straightforward. However, to use existing data requires some data collection and reduction. This segment of the process involves totaling the failure and cost statistics for each period of interest. An example of the basic technique will be

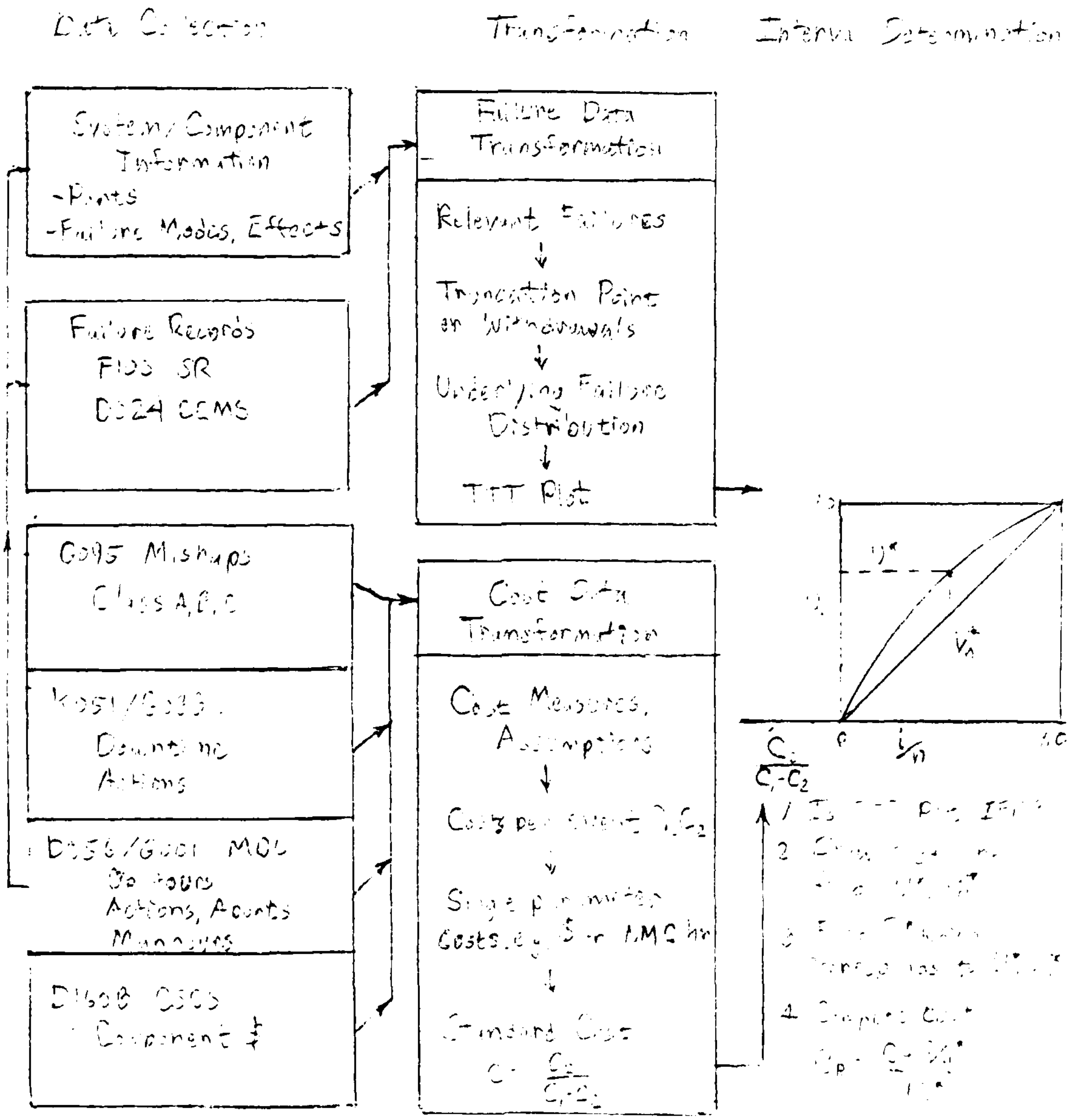


Figure 10: Graphic solution for age replacement

illustrated, and analysis done for the calender year periods 1979-1982.

The intention here is to show credibility of the graphic technique, so failure properties, costs, and interval determination are investigated in more detail than necessary for practical use.

Failure Data Transformation

The ages at failure represent a failure distribution which is incomplete, and subject to change with design, operating location, or season. It is truncated at the age replacement limit for each component. A small number of components may also be replaced at periodic inspections.

The variations in data can be examined through tabulating by year, season, and location, and by looking at trends in D056 statistics. Given a sufficient sample, the data for two years (reflecting design changes), two seasons, or two operating locations could be compared using the F-test. Time series analysis could also be of use for analysis of larger samples.

The age at failure data, though truncated at m components in a sample of n, can be used directly to construct a TTT plot. Barlow and Proschan (2:463) state that the TTT plot, using total time on test T_m for m out of n

components ($\frac{T_i(X)}{T_m(X)} = U_m$) plotted versus i/m, results in a curve which is little different from the plot of $\frac{T_i(X)}{T_n(X)}$ versus i/n for the complete distribution (2:471-472). This is the method that is most convenient in practice.

Another possible approach is to assume the failure distribution is truncated at a proportion equal to m failures out of n total removals, a ratio which can be estimated from D056 reports. Then, the TTT plot could be constructed based on a complete sample size n and a sample total time on test T_n computed from an empirically-fit failure distribution. Barlow and Proschan (2) suggest that this distribution can most easily be found by comparison to reference 'scaled TTT transforms' for parameter ranges of various distributions. Figure 8 showed scaled TTT transforms for the Weibull, gamma, normal, and log-normal distributions. Barlow and Proschan suggest three TTT-based criteria to test the hypothesis of an IFR distribution, and thus candidates for age replacement. These are (1) A difference in total time on test for the sample which exceeds that for the exponential case (45° TTT plot line) by more than the criterion for a given confidence level; (2) The scaled TTT plot for actual sample size m lies above confidence bounds of the exponential distribution.

For n points and N_a=n-1 points above the 45° line, there is (1-1/n) probability that the plot is IFR, and 1/n probability that it is exponential (2:466).

A third approach to failure data transformation is to estimate parameters of a best-fit failure distribution from graphic analysis, then construct a TTT plot for the distribution, plotting the age at failure points as a check. Kao (20:2.2-2.17) describes plotting techniques for the Weibull, gamma, normal, and lognormal distributions. The Kolmogorow-Smirnov and Chi Square tests can be used to check confidence of curve fits.

The analysis here will first show intervals based on direct, truncated-sample TTT plots of the age at failure data and will be assumed IFR where at least m-1 points of the m-point TTT plot are above the 45° line. This will be compared to results for a curve-fit TTT plot, and results for a TTT plot of a failure distribution curve fit. The 1979-82 and 1982 TTT plots can be compared to indicate effects of changes over time, such as design improvement.

The failure data analyses described above assume the failure distribution of the component to be homogeneous. Though it may behave that way, the failure distribution may, in reality, be composed of a number of different failure modes. These may result from causes such as defects in manufacturing or assembly, low cycle/high stress fatigue,

high cycle/low stress, seizure, fatigue, erosion, or fracture. Depending on the components and operating stresses involved, each may result in unique failure mode distributions for a given component, some being DFR, and others being IFR. Those which are DFR, or strictly random, will generally not be relevent to consideration for preventive maintenance. The small difference in TTT plots for truncated versus complete data suggests that truncated age at failure data for a particular failure mode may be used for TTT plots to determine intervals for failure mode oriented tasks. However, it is necessary to use a cost appropriate to the failure mode. The intervals so determined may be worth investigating for the more significant failure modes of a component. However, the distribution of failure consequences and costs is likely to differ considerably between failure modes. Such considerations can be investigated here in an example, but will otherwise be left for future investigations. But to discern failure modes or aggregate them for a component strategy could be troublesome, since occurrence of each failure mode may be related to or preclude the appearance of others.

Cost Data Transformation

The most practical method of estimating costs of failure or replacement events is to use the part cost, mishap loss, direct aircraft down time or labor hours

involved for an event. This is the method to use in practice, assuming that one of the cost elements is of priority concern. However, to verify the method, combined costs will also be used and compared in this study.

Costs such as spare parts, labor, downtime, overhaul, and mishap losses, can be accounted to each component, and summed for the period(s) of interest. These totals can be normalized to costs per failure (repair event C_1 and costs per unfailed replacement event C_2.) The different cost elements can be converted to dollar or availability equivalents, based on fleet statistics in the D056 or K051 data systems.

For example, the loss of an aircraft in a mishap not only costs a proportion of its dollar acquisition cost, but also makes it unavailable for the rest of its expected service life. The non-availability of aircraft also represents a dollar cost because more aircraft are required to achieve the same number of ready aircraft at a given time. Depending on whether availability or dollar cost is the objective, the costs will be in aircraft down time or in dollar cost. Availability costs (down time) can be directly converted to aircraft down-years per 1000 failures, based on fleet down hours per aircraft per year. If an acquisition dollar cost and expected life are known, the dollar cost per 1000 failures can also be expressed as

aircraft down-years per 1000 failures in order to compare dollar and availability costs. The resulting costs C_1 and C_2 are then used to compute the standard cost $C = \frac{C_2}{C_1 - C_2}$.

This can be done for long run average, such as 1979-1982, or over a short time period of interest, for example, the year 1982.

The method used in this study will first use simple costs based on direct aircraft down hours or direct base maintenance labor costs for replacement of an unfailed part. The results can be compared to those based on total component costs, estimated from data system statistics as described above.

Interval Determination

Given the TTT plot and standard cost, the cost line is drawn through the X-coordinate $-C = \frac{-C_2}{C_1 - C_2}$, and tangent to the TTT curve shown in figure 11. This identifies a point (i/n*, U*), which corresponds to the optimum component age limit T*. All the components studied here have records and age limits in hours only, although T* could just as well be another age measure such as LCF stress cycles.

Cost Estimation

The interval determination results in minimum value

of $\frac{n}{T(X_n)}$ $\left[\frac{C + i/n}{U_i}\right]$ (33:9). Since the term $\frac{n}{T(X_n)}$ is constant for the given sample, $\frac{C+i/n}{U_i}$ represents a relative cost parameter. This can be used to compare percent cost variances between different methods of cost and TTT plot derivation. The cost parameter can also be used to compare the non-optimality costs of using dollar measures with an availability objective or using availability measures with a dollar objective. This depends on being able to express both dollar and availability costs in a single parameter. Thus, intervals and costs can be compared for different solution methods, different failure and cost assumptions, and different data sets.

Comparisons

The graphic technique enables rapid comparisons of many alternate cost and failure property estimates for a component. To keep the report to reasonable size, only five of the most significant ones will be examined. These include (1) comparing results of using available failure data and simple costs to those obtained by use of failure distributions and statistical cost analysis; (2) costs and intervals for dollar versus availability objectives; (3) repeatability of the simple versus more refined analysis procedures; (4) comparison of the costs and intervals for different time horizons, in this case data for the

1979-1982 versus 1982 time periods; and (5) estimate of potential benefits in availability or cost which could result from this method, compared to both present intervals and a worst case. The worst case may be defined as use of an interval yielding minimum dollar cost, when the objective is maximum availability (minimum down time), or vice versa.

The cost and failure data transformations described earlier can be easily programmed for computer analysis and recordkeeping. However, manual procedures are emphasized here to show the simplicity, flexibility, and practical use of existing data which is possible with graphic interval determination.

Relevance to Objectives

Results of this analysis effort can be used to answer the three research objectives and questions stated in Chapter I.

The first objective is to show a practical solution procedure. This will be done for the simple case of direct TTT plots of the failure data and simple cost measures of down time and dollars.

The second objective is to explore practical considerations in use of the graphic technique. This includes comparison of cost and interval results for the simple versus the more refined methods of developing TTT plots

and costs which were described previously. Results are generally presented for costs and objectives in both down time and dollars. Another consideration is repeatability of the method, i.e. the variation in results due to rounding and estimation in the analysis procedure. A final aspect examined is difference in interval and cost results which may arise from use of a different time horizon. Here, results based on 1979-1982 and 1982 are compared. The differences indicate the undertainty introduced by using longer time horizons for analysis. In this respect, the graphic technique may be far more responsive and less costly to repeat than age exploration.

The third objective is to estimate potential benefits of the graphic method. The direct benefits are in improvement of aircraft availability or cost reductions at a given point in time. The analysis results can provide a quantitative estimate. Their significance can be evaluated by comparing magnitude of the expected benefits to magnitude of uncertainties in the graphic technique.

CHAPTER IV

SUMMARY OF RESULTS

The graphic technique was used to determine replacement intervals for five F100 engine components - the main fuel pump, engine, speed (N2) sensor, exhaust nozzle control, stator generator, and fuel oil cooler. This chapter describes calculations, results, and practical considerations involved for users of the graphic technique. Their age limits are compared to those determined using the graphic technique. The relative costs are in some cases more than fifty percent less for graphically-determined replacement intervals, and in most cases, between ten and thirty percent.

Information Collected

The components and data sources used in this study have been described in Chapter three. The Appendix provides examples of the data system reports used, lists the failure ages used, and provides the cost data compiled from these sources.

Failure data was collected primarily from the F100 SR data file, with age stated in engine operating hours. While this measure does not necessarily correspond to age of the component, it is the best available from existing Air Force data bases. Design changes have occurred for

each of the components included in this study, and could cause trends in failure properties. In addition, the time of year and operating location may affect the flying environment. Therefore, the ages at failure for each component were charted as shown in Table III, by year, quarter, and unit reporting the failure. Given the small size and long time span covered by the data, a statistical characterization of the trends and periodicities was inappropriate. Both one year and four year data bases were used to provide evidence of any drastic change.

The credibility of the F100 SR file in representing engine failure properties is also difficult to verify, since it contains the only consistent Air Force record of failure ages. Since the data file is oriented toward failure investigations, reports are to some extent by exception, though for some components, all are supposed to be reported. Table IV shows the size of the SR data file as compared to the total number of failures reported in D056. The SR file contained records of between five and twenty percent of all failures. Numerically, the number of reports providing component age at failure did not exceed fifteen in any single year, so the sample size is small for statistical purposes. The representativeness of the sample could still be checked by comparing the relative frequencies of failure modes with those seen statistically.

Table III
Age at Failure Data, Main Fuel Pump

Year	Age at Failure and Reporting Unit			
	Quarter 1	2	3	4
1979 μ= 227 hr	493(1st) 468(36th) 77(36th) 179(1st) 110 -		28 233(405th	
1980 μ=232 hr	366(33rd) 5(405th) 558(1st)	157(33rd) 96 -		561(36th) 105(33rd) 110(56th)
1981 μ=340 hr	424 - 80(36th) 514(33rd)	321(1st) 562(18th) 122(36th)		612(405th) 480(49th) 494(36th) 218(49th) 184(36th) 231(32nd) 375(33rd) 129(48th)
1982 μ=222 hr	70(32nd) 206(57th) 625(405th) 87(36th)	425(36th) 211 - 51 4(36th)	416(48th) 147(49th)	16(405th) 305(405th) 321(405th)
Seasonal Averages:	μ_1=284	μ_2=216	μ_3=206	μ_4=240

Table IV
Comparison of F100 SR and D056 Failures

Component, Year	#SR Reports	#Usable	D056 Total
Main Fuel Pump	81	44	397
1979	12	7	92
1980	13	9	98
1981	30	14	113
1982	26	14	94
N2 Sensor	74	44	817
1979	11	8	225
1980	14	8	216
1981	22	13	211
1982	22	15	165
Stator Generator	39	20	983
1979	9	6	190
1980	4	2	275
1981	6	5	276
1982	20	7	242
Nozzle Control	29	21	569
1979	4	3	132
1980	7	4	140
1981	6	5	137
1982	12	9	160
Fuel Oil Cooler	16	15	169
1979	4	3	37
1980	6	6	51
1981	2	2	39
1982	4	4	42

The appendix provides a breakout of ages at failure by failure mode, which indicates that in general, random or minor discrepancies such as leakage or normal wear are reported proportionately less in the sample. Nevertheless, this is the best failure data base presently available.

The D056, K051, and D160 system reports provided data used to estimate costs. The appendix provides tables showing component-accountable totals for labor, material, and down time for the F-15 fleet. The totals were averaged to obtain the cost per event and per 1000 events, for both failure/repair and age replacement. The data was logged from microfilmed reports, for sixteen consecutive quarters, 1979 through 1982, so that trends and periodicities would be observable. Only gradual trends occurred in flight line actions and labor, but there were occassional jumps in shop actions and labor attributable to modifications. These were excluded from cost computations.

Data base characteristics such as those described above are of interest to a user of the graphic technique in that the results may be affected. However, the results presented here focus on a practical method of using data sources, rather than evaluation of the data base contents.

Analysis Method

The process of graphic interval determination is illustrated in Figure 11. Existing data bases provide

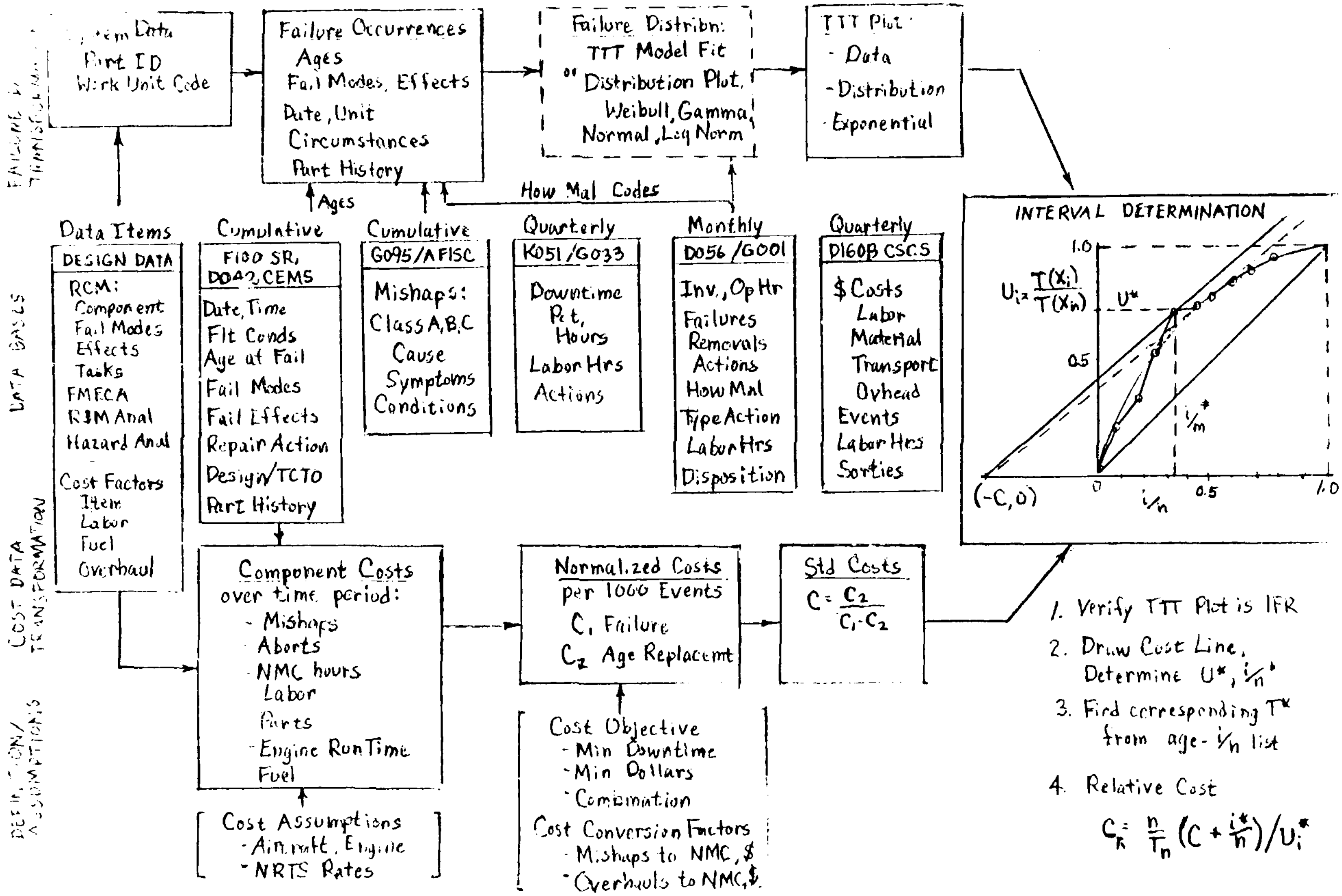


Figure 12: Details of the interval determination process For age replacement, sample truncated at m of n components

ages at failure for construction of a TTT plot and contain numerous maintenance statistics which can be used to develop a standard cost. The interval can be determined by locating the point where a line drawn through $(-\frac{C_2}{C_1-C_2}, 0)$ is tangent to the plotted TTT curve. The relative cost $(C + \frac{i}{n})/U$ can be used to compare costs of different interval lengths on the same TTT plot. To compare costs from different samples of the same component, the expression $C = \frac{n}{Tn} (C+\frac{i}{n})/U$ can be used.

The analysis of failure and cost properties may be simple or comprehensive, depending on needs and preferences of the user. To substantiate consistency and credibility of the graphic technique, both a simplistic and refined method are demonstrated here.

A Simple Method

For a quick analysis, the ages at failure can be plotted directly in TTT form, and costs can be expressed in simple, visible measures such as direct labor hours or aircraft down time accredited to a component.

Failure Data Transformation

A sample of m ages at failure is used as if it is a complete, non-truncated sample of size n. The ages, proportion failed i/m, and number of items (m-i+1) which are still on test can be listed directly. The variable

T_i is the time on test accumulated by the sample components up to the ith failure. It is calculated by successively summing the age difference to the next failure times the number of unfailed items (n-i+1). The time on test for the entire sample is T_m. The variable U_i is the proportion of time on test up to the ith failure. Tables V and VI respectively show the calculations for 1982 and 1979-82 failure data, and the corresponding plots are shown in figures 12 and 13. The plots which lie above the 45° line are increasing failure rate (IFR) and indicate there may be benefit in an age replacement strategy.

Cost Data Transformation

Aircraft down time and direct base maintenance labor provide two simple measures of maintenance cost. The average cost of a failure and repair can be estimated in aircraft not-mission-capable (NMC) hours by computing the ratio of component failures to its unscheduled down time. The average labor cost per failure can be estimated as the ratio of unscheduled labor hours to unscheduled actions for the component, also provided by K051. Aircraft NMC hours and labor hours for age replacement are estimated here by the ratio of total NMC or labor hours for scheduled actions to the number of scheduled actions. The costs computed for each component are shown in Table VII. Using C_1 as cost of failure and C_2 as cost of

Table V
Calculations For TTT Transforms, CY 1982

(a)Main Fuel Pump)

Age	n-j+i	T_j	$U_j=T_j/T_m$	j/m
16	12	192	.067	.083
51	11	577	.200	.167
70	10	767	.266	.250
87	9	920	.320	.333
146	8	1392	.4835	.417
206	7	1812	.629	.500
211	6	1842	.640	.583
305	5	2312	.803	.667
321	4	2376	.825	.750
416	3	2661	.924	.823
425	2	2679	.931	.917
625	1	2879	1.00	1.00

(b)N2 Sensor

Age	n-j+1	T_j	$U_j=T_j/T_m$	j/m
49	15	735	.102	.067
178	14	2541	.353	.133
179	13	2554	.355	.200
215	12	2986	.415	.267
250	11	3371	.468	.333
281	10	3681	.511	.400
359	9	4383	.609	.467
379	8	4543	.631	.533
647	7	6419	.892	.600
661	6	6503	.903	.667
721	5	6803	.945	.733
742	4	6887	.957	.800
807	3	7082	.984	.867
825	2	7118	.989	.933
907	1	7200	1.00	1.00

Table V (cont)

(c)Exhaust Nozzle Control (CENC)

Age	n-j+1	T_i	$U_i=T_i/T_m$	j/m
6	7	42	.013	.143
77	6	468	.144	.286
127	5	718	.220	.429
476	4	2114	.649	.572
797	3	3107	.954	.714
805	2	3121	.958	.857
941	1	3257	1.00	1.00

(d)Stator-Generator

Age	n-j+1	T_i	$U_i=T_i/T_m$	j/m
192	6	1152	.406	.167
194	5	1162	.409	.333
237	4	1334	.470	.500
360	3	1703	.600	.667
888	2	2759	.972	.833
968	1	2839	1.00	1.00

(e)Fuel Oil Cooler

Age	n-j+1	T_i	$U_i=T_i/T_m$	j/m
468	3	1404	.939	.333
471	2	1410	.943	.666
557	1	1496	1.00	1.00

Table VI
Calculations For TTT Transforms, CY 1979-82

(a)Main Fuel Pump

Age	n-j+1	T_j	$U_j=T_j/T_m$	i/m
16	40	640	.057	.025
28	39	1108	.098	.050
51	38	1982	.175	.075
77	37	2944	.260	.100
80	36	3052	.270	.125
87	35	3297	.291	.150
96	34	3603	.318	.175
105	33	3900	.345	.200
110	32	4060	.359	.225
110	31	4060	.359	.250
122	30	4420	.390	.275
129	29	4623	.409	.300
146	28	5099	.450	.325
157	27	5396	.477	.350
179	26	5968	.527	.375
184	25	6093	.538	.400
206	24	6621	.585	.425
211	23	6736	.595	.450
218	22	6890	.609	.475
218	21	6890	.609	.500
231	20	7150	.632	.525
233	19	7188	.635	.550
305	18	8484	.750	.575
321	17	8756	.774	.600
321	16	8756	.774	.625
366	15	9431	.833	.650
375	14	9557	.844	.675
416	13	10090	.892	.700
424	12	10186	.900	.725
425	11	10197	.901	.750
468	10	10627	.939	.775
480	9	10735	.949	.800
493	8	10839	.958	.825
494	7	10846	.958	.850
514	6	10966	.969	.875
558	5	11186	.988	.900
561	4	11198	.990	.925
562	3	11203	.990	.950
612	2	11303	.999	.975
625	1	11316	1.00	1.00

Table VI (cont)

(b)N2 Sensor

Age	n-i+1	T_i	$U_i=T_i/T_m$	i/m	Age	n-i+1	T_i	$U_i=T_i/T_m$	i/m
49	38	1862	.092	.016	597	19	17406	.861	.526
128	37	4785	.237	.053	620	18	17820	.881	.553
133	36	4965	.246	.079	635	17	18075	.894	.579
133	35	4965	.246	.105	647	16	18267	.903	.605
179	34	6495	.321	.132	647	15	18267	.903	.632
215	33	8013	.396	.158	661	14	18463	.913	.658
250	32	9133	.452	.185	663	13	18489	.915	.684
250	31	9133	.452	.211	692	12	18837	.932	.711
287	30	10243	.507	.237	695	11	18870	.933	.737
359	29	12331	.610	.263	721	10	19130	.946	.763
360	28	12359	.610	.289	728	9	19193	.949	.789
379	27	12872	.637	.316	742	8	19305	.955	.816
383	26	12976	.642	.351	794	7	19669	.973	.842
393	25	13226	.654	.368	807	6	19747	.977	.868
405	24	13514	.688	.395	825	5	19837	.981	.895
408	23	13583	.672	.421	876	4	20041	.991	.921
429	22	14045	.695	.447	882	3	20059	.992	.947
439	21	14255	.705	.474	907	2	20109	.995	.974
588	20	17235	.852	.500	1019	1	20221	1.00	1.00

Table VI (cont)

(c) Convergent Exhaust Nozzle Control (CENC)

Age	n-i+1	T_i	$U_i=T_i/T_m$	i/m
77	14	1078	.161	.071
127	13	1728	.258	.143
133	12	1800	.269	.214
157	11	2064	.309	.285
278	10	3274	.489	.356
279	9	3283	.491	.429
281	8	3299	.493	.500
476	7	4664	.697	.571
719	6	6122	.915	.642
746	5	6257	.935	.714
797	4	6461	.966	.786
805	3	6485	.970	.857
873	2	6621	.990	.929
941	1	6689	1.00	1.00

(d) Stator-Generator

Age	n-i+1	T_i	$U_i=T_i/T_m$	i/m
33	19	627	.068	.053
192	18	3489	.380	.105
194	17	3523	.384	.158
224	16	4003	.437	.211
237	15	4198	.458	.263
244	14	4436	.484	.316
280	13	4904	.535	.368
360	12	5864	.639	.421
449	11	6843	.746	.474
450	10	6853	.747	.526
501	9	7312	.797	.579
520	8	7464	.814	.632
646	7	8346	.910	.684
673	6	8508	.928	.737
682	5	8533	.931	.789
711	4	8649	.943	.842
798	3	8910	.972	.894
888	2	9090	.991	.947
968	1	9170	1.00	1.00

(e) Fuel Oil Cooler

Age	n-i+1	T_i	$U_i=T_i/T_m$	i/m
35	9	315	.070	.11
313	8	2539	.563	.22
468	7	3624	.804	.33
471	6	3642	.808	.44
575	5	3662	.812	.56
584	4	3698	.820	.67
722	3	4112	.912	.78
847	2	4362	.967	.89
995	1	4510	1.00	1.00

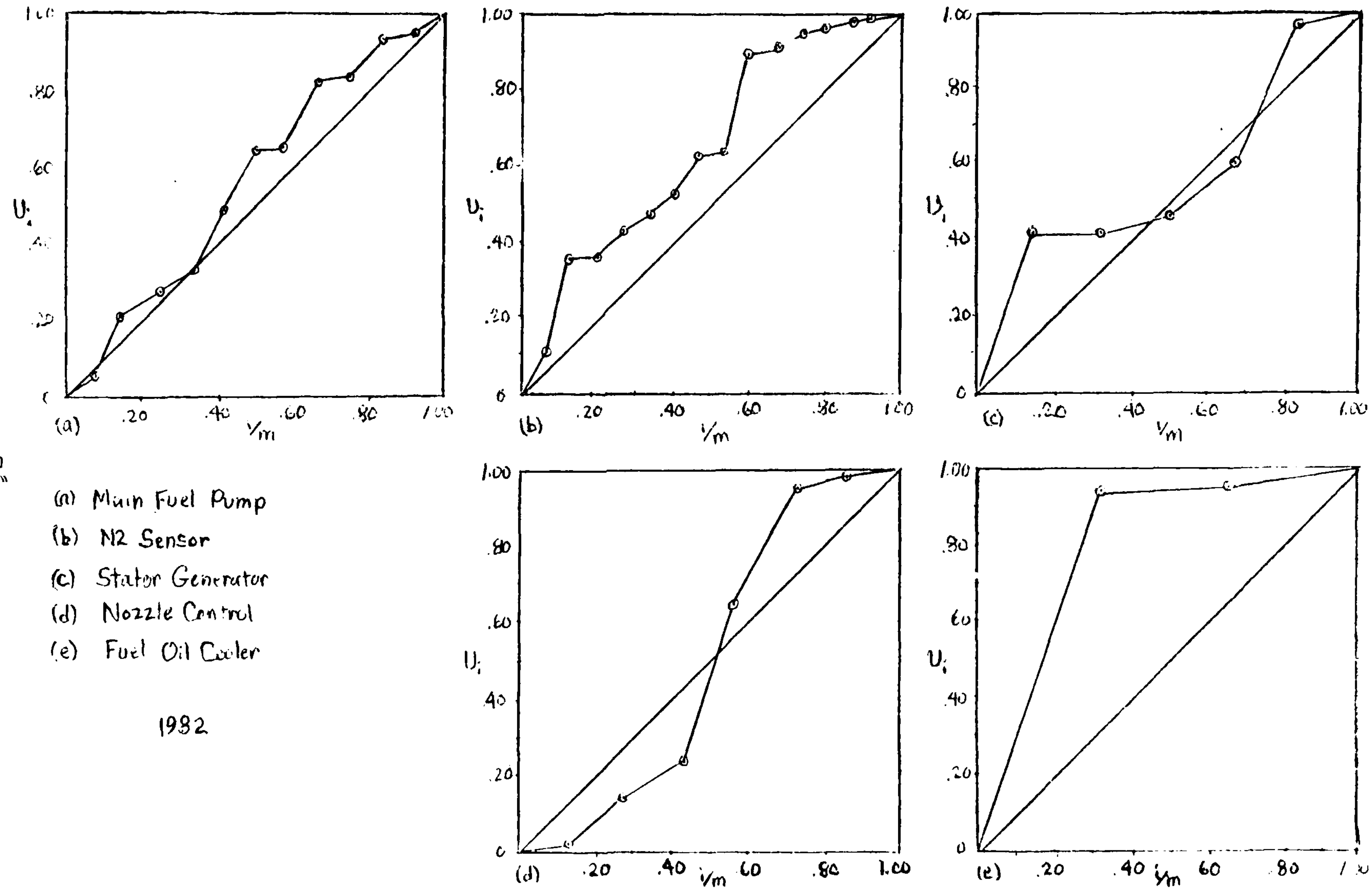


Figure 12: Total Time on Test (TTT) plots for five F100 components, CY 1982

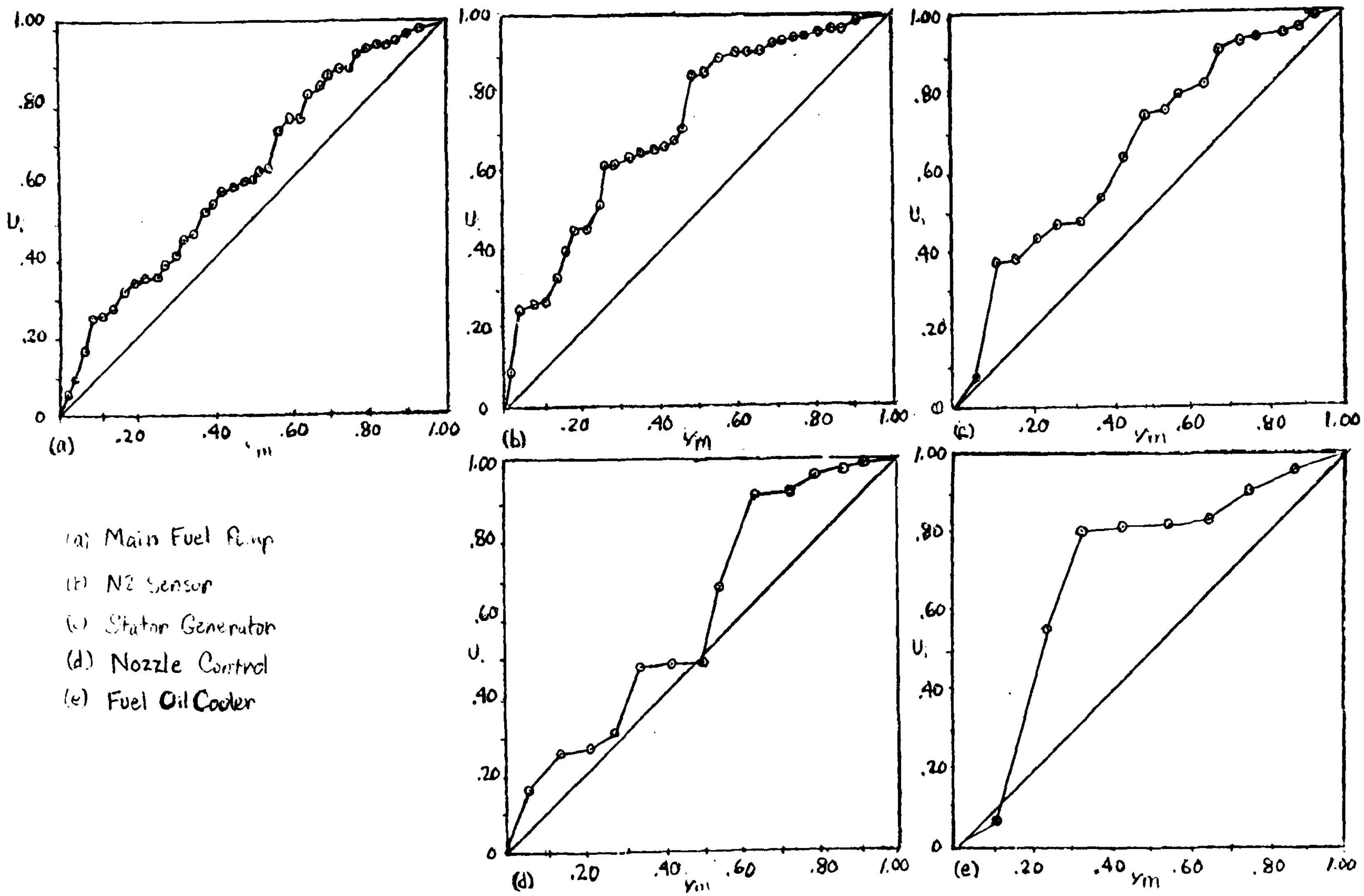


Figure 13: Total Time on Test (TTT)plots for five F100 components
CY 1979-1982

Table VII
Direct Cost Measures From Data

Cost Element	Fuel Pump	N2 Sensor	CENC	Generator	Oil Cooler
<u>Failure and Repair</u> C_1					
Aircraft NMC hours	5.7	3	3.5	1.7	4.8
Labor Hours	15	4	10	5	15
<u>Age Replacement</u> C_2					
Aircraft NMC hours	2	1	2	1	2
Labor Hours	5	2	5	2	3

replacement, the standard cost is computed as the ratio $\frac{C_2}{C_1-C_2}$. Table VIII shows these standard costs for each of the parts.

Interval Determination

The optimum interval is identified by drawing a line through the point (-C , O) and tangent to the TTT plot, as illustrated in figure 11. The point of tangency is a point (i/m*, U*), which corresponds to an interval T*. The interval can be estimated from the table of values used for constructing the TTT plot. Table IX shows the values of U*, i/m*, and T* found for each component. The standard costs in aircraft down hours differ considerably from those in labor hours, but the resulting intervals are still the same because of extreme points on the TTT plots (see Figures 12 and 13.) The intervals determined using the 1982 data base do not differ greatly from those based on 1979-1982 data except for the least expensive of the components, the generator and N2 speed sensor.

Cost Comparison

The costs associated with intervals can be compared for the same sample by computing $(C + i/m)/U_i$, which is minimized at the tangency point (i/m*, U*). The present replacement interval for each component is beyond the greatest age at failure, in these truncated samples, so

Table VIII
Standard Costs

Cost Measure	Fuel Pump	N2 Sensor	CENC	Generator	Oil Cooler
Aircraft NMC hours	.54	.50	1.33	1.43	.714
Labor Hours or $	.50	1.00	1.00	.67	.25

Table IX
Optimum Intervals
Simple Procedure

Component	1982 U*	1982 i/m*	1982 T*	1979-1982 U*	1979-1982 i/m*	1979-1982 T*
Main Fuel Pump	.82	.66	420	.88	.70	420
N2 Sensor	.90	.60	810	.87	.50	600
Nozzle Control	.95	.67	700	.92	.63	710
Stator-Generator	.97	.85	900	.92	.64	650
Fuel Oil Cooler	.97	.85	900	.92	.64	650

*Same for both objectives of NMC hours and labor $

AD-A135 637 PREVENTIVE MAINTENANCE INTERVALS FOR COMPONENTS OF THE F-15/F100 AIRCRAFT ENGINE(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF SYST.. J R BRILL 2/2

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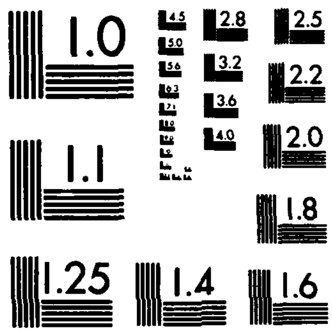

MICROCOPY RESOLUTION TEST CHART
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the value of i/m used is 1. The relative costs computed using this approach are shown in Table X. If the results are representative for the component, cost savings of up to fifty percent may be possible.

Limitations

The simple approach described above is restricted in how well actual failure properties and costs of a component are represented. The TTT plot for a truncated sample, such as those here, does reflect the underlying failure distribution. However, the greatest age in the sample will usually be less than the existing age replacement limit, and perhaps biased toward a shorter interval. The cost measures used may also be improved. Direct down time and labor hours accounted to a component may not fully represent support impacts of a component, since these may also include mishaps, engine removals, and engine life used in testing. To assess the importance of these considerations, a refined graphic procedure may be used, one which considers the underlying failure distribution and cost elements in more detail.

Refined Method of Interval Determination

Both failure and cost properties of each component may be more realistically described than above.

Failure Data Transformation

The TTT plot reflects the underlying failure

Table X
Computation of Relative Costs

Cost Measure	Fuel Pump		N2 Sensor		CENC		Generator		Oil Cooler	
	C_T	C_{T*}	C_T	C_{T*}	C_T	C_{T*}	C_T	C_{T*}	C_T	C_{T*}
1982										
Aircraft NMC hr	1.54	1.46	1.50	1.22	2.33	2.10	2.43	2.40	1.71	1.12
Labor $	1.50	1.41	2.0	1.77	2.0	.856	1.67	1.60	1.25	.623
1979-1982										
Aircraft NMC hr	1.54	1.40	1.50	1.14	2.33	2.13	2.43	2.25	1.71	1.04
Labor $	1.50	1.36	2.00	1.72	2.00	1.77	1.67	1.40	1.25	.725

C_T = relative cost at present interval C_{T*} = relative cost at graphic solution

where $C_T = (C+i/n)/U_i$ within a sample

distribution of a sample, in its shape, but is altered in values where parts are replaced unfailed at an existing age limit. Such is the case for all five of the components considered here. To evaluate this effect, the sample of m failures is considered to represent m failures out of n components in the complete sample. A representative failure distribution can be identified from comparison with model TTT plots and its numeric parameters estimated graphically. The curve fit can be verified by an appropriate statistical test such as chi-square or Kolmogorov-Smirnov. The TTT plot can then be constructed for a complete distribution and total time on test.

The first step is to estimate or assume the cumulative percent failed at which the sample has been truncated. Here, the percent failed is assumed to correspond to the ratio of failures to total removals which is reported in D056. As shown in Table XI, this truncation ratio m/n is considerably less than one for each of the components. The parent sample size n is computed assuming m to be the number of failures. This new, larger sample size used as the basis for the next step of plotting the failure distributions.

The main fuel pump 1981 data is used here to illustrate how TTT plots for complete failure distributions are developed from the truncated failure data sets of each

Table XI
Estimation of Sample Size For Truncated Data

Component	#Failed	Mal/Other	Ratio m/n	Actual/m	Equiv.n
Fuel Pump					
1979	92	80	.535	7	12
1980	98	58	.628	8	12
1981	113	91	.554	14	24
1982	94	90	.511	13	25
N2 Sensor					
1979	225	25	.900	8	8
1980	216	16	.931	7	7
1981	211	21	.909	10	10
1982	166	35	.826	15	17
Stator Gen.					
1979	190	74	.720	6	7
1980	275	41	.870	2	2
1981	276	35	.887	5	5
1982	242	71	.773	6	7
Nozzle Control					
1979	132	81	.720	3	4
1980	140	112	.870	4	6
1981	137	57	.887	5	6
1982	160	100	.771	7	10
Fuel Oil Cooler					
1979	37	38	.493	4	5
1980	51	33	.607	6	9
1981	39	32	.549	2	3
1982	42	34	.553	3	5

component. The first step is to identify the distribution. In this case, normal, lognormal, and Weibull plots were constructed, and a Weibull plot provided the best fit, shown in Figure 14. This was confirmed by the chi-square test as shown in Table XII. The failure distributions for each component and year were them plotted, and found to fit a Weibull distribution fairly well in each case. This is a cumulative failure distribution function defined by

$$F(T) = e^{(\frac{-T}{n})^{\beta}}$$

where T is component age, n is the characteristic life, and β is a shape parameter.

The Weibull parameters estimated for each component failure sample are listed in Table XIII. The shape parameters vary considerably from the exponential case of β=1.0. The characteristic life also differs merkedly from mean time between failure (MTBF), its equivalent in the more restrictive case of an exponential failure distribution. Table XIII lists the MTBFs from the RCM analysis and D056 failure totals for comparison. The parameter μ is an age below which no failures occur, and μ is expected life of the component.

Given the failure distribution parameters β, an index of cumulative percent failed can be constructed, and used to find ages T of the distribution which correspond to the ages at failure in the sample data, as shown in

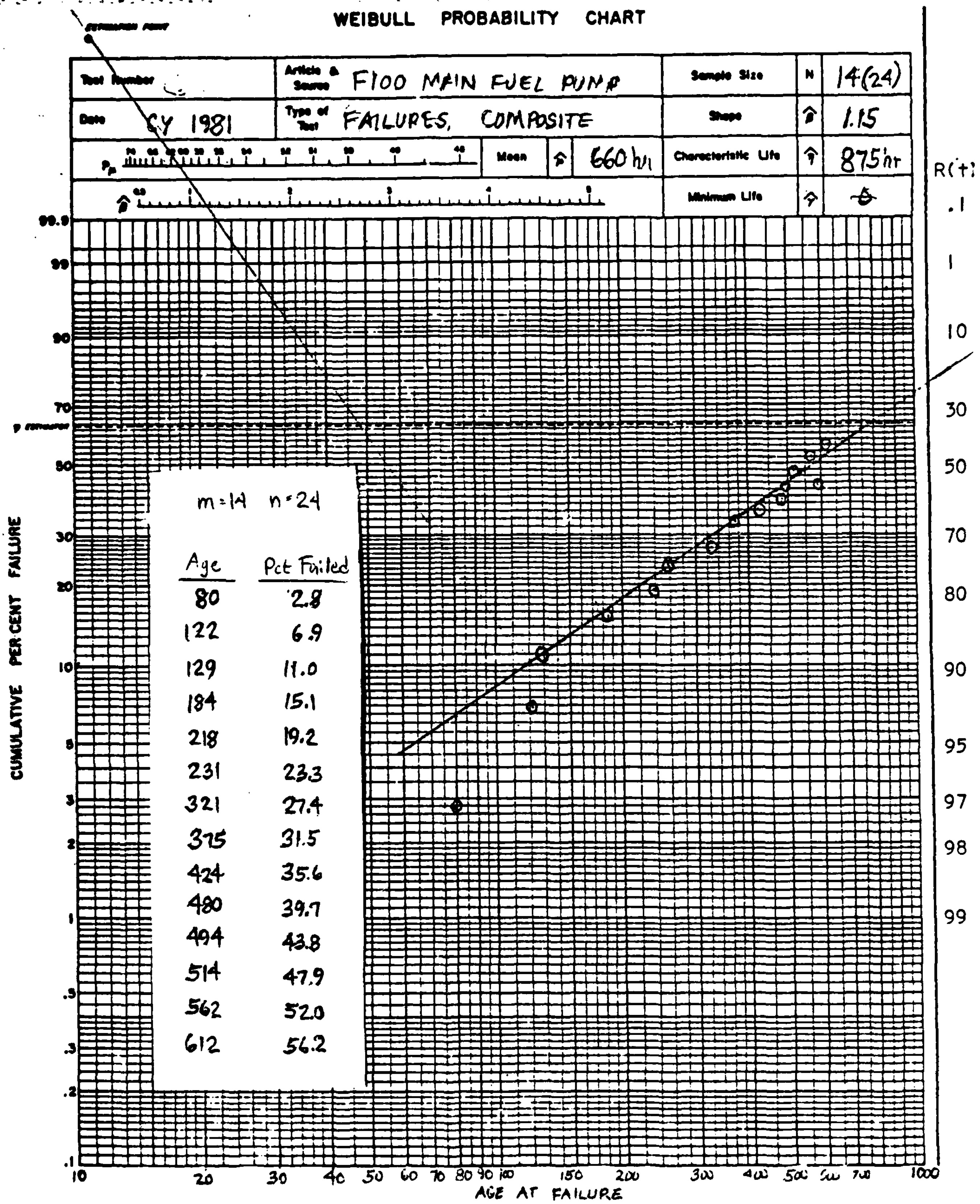


Figure 14: Ages at failure and Weibull plot for F100 fuel pump.

Table XII
Chi-Square Test For Failure Distribution
Main Fuel Pump, CY 1981

Criterion: Max allowable sum of squared differences of sample ages to age t

Actual sample size m=14; degrees of freedom $\gamma=13$

Statistic: $X^2 = \sum_m \frac{(t_o-t)^2}{t}$

Age	$\left[(t_o-t)^2/t\right]_i$	=	δ_i
80	$40^2/40$		40.0
122	-		0
129	$37^2/85$		16.1
184	$4^2/180$		.09
218	$13^2/205$		.82
231	-		0
321	$21^2/300$		1.47
375	$15^2/360$		.62
424	$24^2/400$		1.44
480	$50^2/430$		5.81
494	$4^2/490$		.03
514	$16^2/530$		.48
562	$38^2/600$		2.41
612	$58^2/670$		5.02
			64.28

$$X^2 = \frac{i}{m} \sum_{i=1}^{m} \delta_i = \frac{64.28}{14} = 5.58$$

satisfies 95% confidence criterion that distribution is Weibull.

Table XIII
Results of Failure Distribution Analysis

Component, Year	#Fail	Equiv n	*Weibull Parameters β	η	γ	μ	RCM MTBF	D056 MTBF
1. Main Fuel Pump m/n=(.554)								
1979-82 Overall	42	76	1.20	775	0	700	901	1188
1979	7	12	.82	675	0	770	901	1066
1980	8	12	.70	700	0	850	901	1081
1981	14	24	1.15	800	0	730	901	1098
1982	13	25	.70	900	0	1200	901	1945
2. N2 Sensor m/n=(.893)								
1979-82 Overall	40	44	1.30	675	0	625	1122	576
1979	8	8	3.10	650	80	330	1122	436
1980	7	7	2.50	520	13	475	1122	491
1981	10	10	1.33	550	0	470	1122	588
1982	14	18	1.20	675	0	412	1122	863
3. Generator m/n=(.816)								
1979-82 Overall	19	23	1.50	700	0	625	892	479
1979	6	7	2.60	600	45	580	892	516
1980	2	2	1.35	570	0	520	892	385
1981	5	5	0.82	660	0	700	892	449
1982	7	7	1.30	675	0	625	892	592

Table XIII(cont)
Results of Failure Distribution Analysis

Component, Year	#Fail	Equiv n	*Weibull Parameters β	η	γ	μ	RCM Av.Life	D056 Av.Life
4.Nozzle Control (.619)								
1979-82 Overall	19	30	.70	1300	0	1450	1186	829
1982	7	10	.95	1100	0	1250	1186	894
5.Fuel Oil Cooler(.553)								
1979-82 Overall	15	26	1.35	1250	0	1000	4700	2780
1979-82 W/O Burst	9	16	1.65	1100	18	950	4700	2980

*Weibull Parameters

$F(T) = -(\frac{T}{\eta})^{\beta}$

F(T) = Cumulative percent failed to age T

β = shape parameter, $\beta > 1$ increasing failure rate; $\beta = 1$ is exponential

η = characteristic life, hours

γ = failure free life, hours

μ = expected life, hours

T = age, op hours

Table XIV. This provides a total time on test for the entire sample of size n. A TTT plot can then be constructed for the complete distribution, as shown in figure 15. Figures 16 and 17 show the TTT plots constructed for the 1982 and 1979-1982 data sets for each component.

<u>Cost Data Transformation</u>

The costs attributed to a component can be estimated in many different ways, using different assumptions. The data sources and totals are presented in the appendix. Table XIV showed costs per thousand failure or replacement events derived from them.

The cost elements are grouped to reflect availability loss, or dollar costs per failure of the components. Availability measurement may include the loss of equivalent aircraft due to mishaps or aborts. Dollar costs may include aircraft loss or engine overhauls as material costs, as well as engine life and fuel consumed in test runs.

To express such costs in only availability or dollars may require assumptions about cost factors. The assumptions about engine costs are that fuel is $.16 per pound, burned at 3000 pounds per hour in test runs, and that engine life is 1300 hours. The average test cell time is assumed to be 2 hours per removal. Trims are assumed to occur for half of all pump, or N2 sensor replacements, a third of nozzle

Table XIV
Use of Curve Fit to Provide Overall TTT Sum

(1)Weibull Plot
β=1.15, η=800

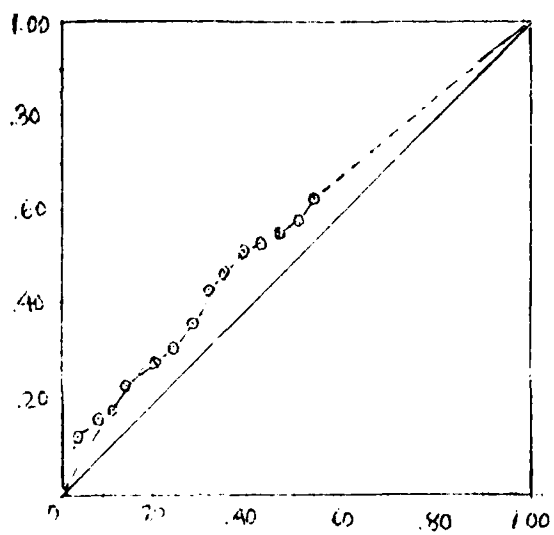
(2)Age-% Failed Index

Age	$-(T/\eta)$	% Failed
25	.0186	.018
50	.0411	.040
75	.066	.064
100	.092	.087
200	.203	.184
300	.324	.277
400	.451	.363
500	.582	.441
600	.718	.512
700	.858	.585
800	1.00	.632
900	1.15	.682
1000	1.29	.725
1100	1.44	.764
1200	1.59	.796
1300	1.75	.826
1400	1.90	.850
1500	2.06	.873
1600	2.22	.891
1700	2.40	.909
1800	2.54	.921
1900	2.70	.933
2000	2.87	.945
2100	3.03	.952
2200	3.20	.959
2400	3.54	.971
2700	4.05	.983

(3)Weibull Ages for i/η, η=24

n	%Fail	Age	n-j+1	T_i	U	i/N
1	.0285	37	24	1888	.050	.042
2	.0689	78	23	1831	.102	.033
3	.1099	124	22	2843	.159	.125
4	.1509	166	21	3725	.208	.167
5	.192	209	20	4585	.257	.205
6	.2330	253	19	5421	.303	.250
7	.274	297	18	6213	.348	.292
8	.3151	344	17	7012	.435	.333
9	.3562	392	16	7780	.435	.375
10	.3973	444	15	8560	.479	.417
11	.4384	496	14	19288	.520	.458
12	.4795	595	13	10055	.563	.308
13	.521	612	12	10739	.600	.542
14	.562	668	11	11355	.635	.583
15	.603	738	10	12055	.674	.675
16	.644	824	9	12829	.688	.667
17	.685	907	8	13576	.760	.708
18	.726	1003	7	14248	.797	.750
19	.767	1109	6	14884	.834	.792
20	.8081	1240	5	15539	.869	.883
21	.849	1396	4	16163	.904	.875
22	.890	1594	3	16757	.934	.913
23	.9310	1883	2	17355	.971	.958
24	.9715	[illegible]	[illegible]	17872	1.00	1.00

TTT Sum T_i = 17872



Actual Data

Age	n- i+1	T_i	U_i	i/n
80	24	1920	.108	.042
122	23	2886	.162	.083
129	22	3040	.170	.125
184	21	4195	.235	.167
268	20	4875	.273	.208
231	19	5122	.287	.250
321	18	6742	.377	.292
375	17	7660	.429	.333
424	16	8444	.472	.375
480	15	9284	.519	.417
494	14	9480	.531	.458
514	13	9740	.545	.500
562	12	10316	.565	.542
612	11	10866	.608	.583

(T_n = 17872)

Figure 15. Total Time on Test plot and computations, F100 main fuel pump, 1981

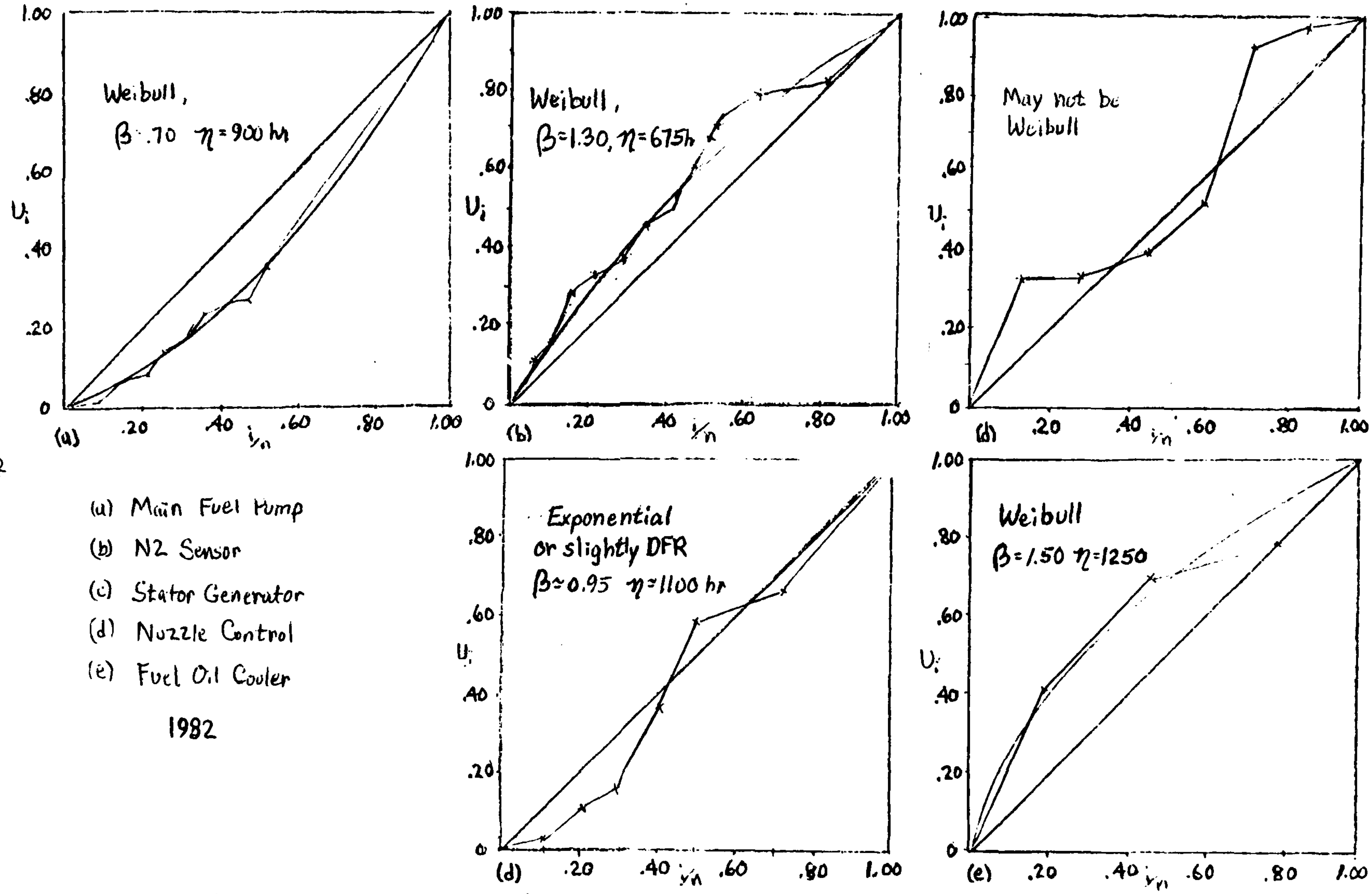


Figure 16: Total Time on Test (TTT) plots for complete distributions, 1982

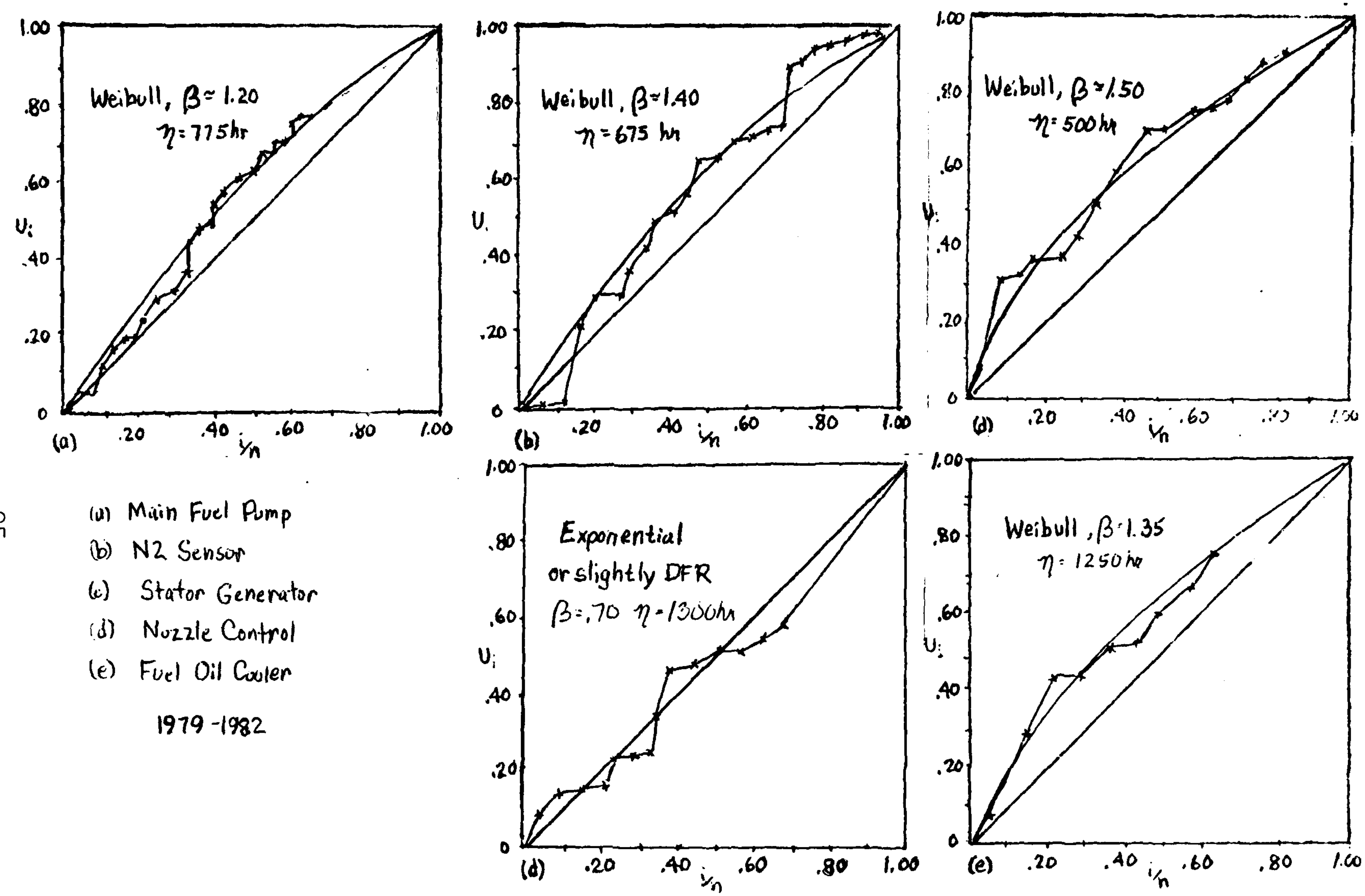


Figure 17: Total Time on Test (TTT) plots for complete distributions, 1979-1982

control replacements, and a tenth of oil cooler or generator replacements. The engine contribution to downtime is assumed to be in proportion to its share of total aircraft downtime reported in K051, 5.9% for 1979-1982, and 2.41% for 1982.

Aircraft losses in mishaps cost downtime, assumed to be ten years for a Class A mishap (unrecoverable), a tenth of a year for a class B mishap (damage), a hundreth of a year for a class c (emergency), and a thousandth of a year per abort. This can be converted to NMC hours by using the statistical average of 30929 down hours per aircraft-year. A second assumption is used to express mishap costs in dollars. An F-15 is assumed to cost 22 million dollars and last 20 years, meaning a cost of $1.1 million per aircraft year. The same relative magnitudes are used for the different grades of mishaps and aborts.

The results of Table XV for costs of failure indicate that the costs of NMC aircraft dominate availability measurements, and that costs of material (aircraft lost engines, parts) dominate the dollar cost. Table XVI shows costs developed for age replacement, using the same cost factors as for failure costs, except that the NMC hours accountable are mostly reported as scheduled in the K051 report.

Table XV
Costs per 1000 Failures

(a) CY 1982-Availability Costs

Cost Element	Fuel Pump	N2 Sensor	CENC	StatorGen	Cooler
Mishaps A	0	0	0	0	0
B	0	0	0	0	0
C	.170	.060	0	0	0
Aborts	.040	.042	.025	.049	.024
	.210	.102	.025	.049	.024
NMC A/C hr	5662	4640	3556	1425	8830
NMC Engines (Indirect hr)	670	229	22	7	0
.0241 x 72 x base .0241 x 1440 x ovh	6332	4869	3578	1432	8830
Combined Total	12693	7950	4333	2912	9555

\- Dollar Costs

Cost Element	Fuel Pump	N2 Sensor	CENC	StatorGen	Cooler
Material					
Aircraft	$.187M	$.066M	$.028M	$.054M	$.026M
Engines	8.50	3.00	0	0	0
Items ovhl	27.0	3.73	13.0	3.37	3.95
Labor					
Base	1.936	.347	2.182	.179	.849
Depot	.843	.338	.506	.338	.506
Engine Life	.210	.201	.138	.039	.039
Fuel.	.262	.251	.171	.048	.048
Transport					
Engines	.034	.012	0	0	0
Items	.020	.006	.014	.020	.020
Base Overhead (D160B)	.335	.250	.350	.121	.287
Combined Total	$39.33M	$8.20M	$16.39M	$4.17M	$5.73M

Table XV (cont)
(b) CY 1979-1982

- Availability Costs

Cost Element	Fuel Pump	N2 Sensor	CENC	StatGen	Cooler
Mishaps A	0	0	0	0	0
B	1.26	.612	.203	0	0
C	.034	.098	.041	.018	.059
Aborts	.076	.049	.046	.023	.047
Sub Total	1.370	.759	.290	.041	.106
NMC A/C hr	14627	10398	5464	4486	3144
NMC Engine: (Indirect NMC hr)	4241	317	1113	261	659
	18870	10715	6577	4747	3803
Combined Total*	60256	33330	15337	5986	7005

30200 NMC hr = 1 Aircraft down year (A/C yr)

- Dollar Costs

Cost Element	Fuel Pump	N2 Sensor	CENC	StatGen	Cooler
Material					
Aircraft	$1.507M	$.834M	$.044M	$.319M	$.117M
Engines	12.09	1.71	1.41	.610	3.55
Items orhl	27.0	3.73	13.0	3.37	3.95
Labor					
Base	.325	.275	.380	.139	.350
Depot	.843	.338	.506	.338	.506
Engine Life	.432	.391	.262	.079	.104
Fuel	.548	.488	.326	.098	.130
Transport					
Engine Orhl	.049	.006	.007	.003	.014
Item Ovhl	.002	.006	.014	.020	.020
Overhead (D160B rate)	.335	.250	.350	.121	.287
Combined Total	$43.13M	$8.02M	$16.30M	$5.10M	$9.03M

Table XVI
Costs per 1000 Age Replacements

Cost Element	Fuel Pump	N2 Sensor	CENC	StatorGen	Cooler
Mishaps	-	-	-	-	-
NMC A/C hr	3500	1000	1500	1000	2500
Combined Total	3500hr	1000	1500	1000	2500

(b) Dollar Costs

Cost Element	Fuel Pump	N2 Sensor	CENC	StatorGen	Cooler
Material Item	27.0M	$3.73M	$13.0M	$3.37M	$3.95M
Labor					
Base	.08	.025	.036	.025	.063
Depot	.843	.338	.506	.338	.506
Engine Life	.15	.15	.08	.10	.05
Fuel	.187	.20	.11	.137	.068
Transport Item	.02	.006	.014	.02	.02
Overhead	.084	.019	.030	.019	.050
Combined Total	$18.36M	$4.47M	$13.78M	$4.01M	$4.71M

The costs of failure and replacement in Tables XV and XVI are next used to compute the standard costs. These are listed in Table XVII. For comparison, availability costs are expressed in both aircraft NMC hours alone, and as a total including contributions from engine removals and mishaps. The dollar costs are shown for both parts alone, and the combined total for all the dollar cost terms.

Interval Determination

The first check is to verify that the TTT plot indeed represents an IFR distribution. In most of the cases plotted here, the plot was all above the 45° line (IFR) or all below it (DFR). In such cases, the probability is only i/n that the distribution is exponential (2:469).

Where a TTT plot crosses the 45° line, the crossing test described by Barlow and Campo (2:468) is helpful. They show the probabilities for four events given that the distribution is exponential:

1. The plot is initially below and finally below the 45° line

2. The plot is initially below and finally above the 45° line

3. The plot is initially above and finally below the 45° line.

4. The plot is initially above and finally above the 45° line.

Table XVII
Standard Costs For Graphic Solution

(a) For Availability Loss Measures

Measure	Fuel Pump	N2 Sensor	CENC	Gen	Cooler
A/C Down Hr					
1982	1.62	.275	.730	2.35	.395
1979-82	.315	.106	.378	.287	3.88
Combined Total					
1982	.381	.144	.529	.523	.354
1979-82	.071	.031	.108	.201	.555

(b) For Dollar Cost Measures

Measure	Fuel Pump	N2 Sensor	CENC	Gen	Cooler
Material Cost					
1982	3.11	1.214	-	-	-
1979-82	2.0	1.47	8.97	3.63	1.08
Combined Total					
1982	2.59	1.20	5.28	4.21	4.62
1979-82	1.92	1.26	5.47	3.68	1.09

the validity of the TTT plots, standard costs, the intervals, and their relative costs.

A comparison of the TTT plots for the simple and refined procedures indicates strong differences. For example, the 1982 TTT plot for the main fuel pump is IFR when truncated data is directly plotted as in figure 12(a), but DFR when its plot is based on a complete Weibull distribution as in figure 16(a). The plots based on truncated data in figures 12 and 13 generally reflect a more positive curvature of the plot than in the TTT plots of figures 16 and 17 which are based on the full distribution. This agrees with Barlow's note that IFR TTT plots become more so when truncated, i.e. stochastically cominating the exponential. Conversely, DFR plots are dominated by the exponential.

The optimal interval computations of i/n*, U*, T* and (C+i/n*)/U* are shown inTable XVIII for the given standard costs. Table XIX shows current costs, based on i/n and U which correspond to the current interval.

Intervals determined for the simple and refined procedure are compared in Table XX. Results for the refined procedures appear to be more sensitive to changes in the objective. The simple procedure cannot define an interval beyond the existing age replacement limit, except if failures are allowed beyond the limit, for data collection.

Table XVIII
Optimal Intervals-Computations

(a) 1982

Component	C	i/n*	U*	T*	(C+i/n*)/U*
Main Fuel Pump					
Availability	.381	DFR		-	1.381
Dollars	2.59	DFR		-	3.59
N2 Sensor					
Availability	.144	.57(.54)	.68(.72)	575(800)	1.05(.95)
Dollars	1.20	1(.64)	1(.82)	1500(875)	2.2(2.24)
Nozzle Control					
Availability	.529	Exponential		-	1.53
Dollars	5.28	or DFR		-	6.28
Stator Generator					
Availability	.523	.73	.93	900hr	1.35
Dollars	4.21	.90	.98	1500hr	5.21
Fuel Oil Cooler					
Availability	.354	.47	.70	600hr	1.18
Dollars	4.62	1	1	-	5.62

( ) shows value based on the actual data in the case where is is markedly different from the distribution

TableXVIII (cont)

(b) 1979-82

Component	C	i/n*	U*	T*	(C+i/n*)/U*
Main Fuel Pump					
Availability	.071	.65	.78	750	.92
Dollars	2.0	1	1	-	3.0
N2 Sensor					
Availability	.031	.48	.67	500	.763
Dollars	1.47	.80	.94	1500	2.41
Nozzle Control					
Availability	.108	(.47)	(.38)	550(700)	1.52
Dollars	8.97	1	1	-	9.97
Stator Gen					
Availability	.201	.39	.58	450	1.02
Dollars	3.63	1	1	2000	4.63
Oil Cooler					
Availability	.555	.90	.95	1800	1.53
Dollars	1.08	1	1	-	2.08

Table XIX
Costs of Current Task Intervals

Component	T	i/n	U	C Avail	C $	(C+i/n)/U Avail	(C+i/n)/U $
Main Fuel Pump	680						
1982		.55	.52	.381	2.59	1.79	5.88
1979-82		.58	.63	.071	2.0	1.03	4.095
N2 Sensor							
1982	1000	.80	.86	.144	1.20	1.097	2.32
	1500	.93	.98			1.095	2.17
1979-82	1000	.84	.94	.031	1.47	.959	2.49
	1500	1	1			1.031	2.47
Nozzle Control							
1982	750hr	.60	.514	.529	5.28	2.20	11.43
	900hr	.67	.64			1.87	9.30
1979-82	750hr	.50	.54	.108	8.97	1.125	17.54
	900hr	.61	.59			1.216	16.23
Stator Gen	1000						
1982		1	1	.523	4.21	1.523	5.21
1979-82		1	1	.201	3.63	1.201	4.63
Oil Cooler	1250						
1982		-	-	.354	4.62	1.35	5.62
1979-82		.72	.80	.555	1.08	1.59	2.25

Table XX
Interval Comparisons

(a) 1982 Data

Component	Interval: Current	Simple	Refined
Fuel Pump			
Availability	680	420	DFR
Dollars(Labor)	680	(420)	DFR
N2 Sensor			
Availability	1000/1500	810	850
Dollars	1000/1500	(810)	1500
Nozzle Control			
Availability	750/900	700	1100
Dollars	750/900	(700)	1100
Generator			
Availability	1000/2000	900	900
Dollars	1000/2000	(900)	1500
Oil Cooler			
Availability	1250	470	600
Dollars		(470)	1250

DFR = decreasing failure rate; / indicates a 2nd interval

( ) indicates standard cost $C >> 1$

Table XX (cont)

(b) 1979-1982 Data

Component	Current	Interval Simple	Refined
Fuel Pump			
Availability	680	420	750
Dollars	680	420	*
N2 Sensor			
Availability	1000/1500	600	500
Dollars	1000/1500	600	1500
Nozzle Control			
Availability	750/900	710	550(700)
Dollars	750/900	710	
Stator Generator			
Availability	1000/2000	650	500
Dollars	1000/2000	650	2000
Fuel Oil Cooler			
Availability	1250	475	1800
Dollars	1250	475	*

* The standard cost was so great that i/n* = 1.0

The refined procedure requires analysis of the failure distribution, but in many cases, this is known from other reliability studies. Either procedure requires a statistically representative set of failure data.

A final comparison is relative cost. The relative costs of current intervals are listed in Table XXI with the corresponding cost of intervals determined using the simple and refined procedures. This table indicates that cost savings due to improved interval determination are considerable, using either the simple or refined procedure. This is confirmed by computing the cost reductions in percent, as shown in Table XXII . These range from about three to fifty seven percent cost reductions through use of graphic interval determination.

Credibility of the Graphic Technique

The results presented here indicated that use of the graphic technique should yield considerable direct benefits in cost. The data base examined here is not adequate for a statistical assessment of this. However, the results here to shed light on characteristics of the graphic model and technique that a user should consider.

First, the model is unbiased and assures a consistent relationship between task interval and the maintenance management objective. Present methods lack this, which is seen in the comparisons of costs and intervals.

Table XXI
Relative Costs of Replacement Intervals

(a) Availability

Component	Current		Simple		Current		Refined	
	1982	79-82	1982	79-82	1982	79-82	1982	79-82
Main Fuel Pump	1.54	1.54	1.46	1.40	1.79	1.03	1.38	.92
N2 Sensor*	1.50	1.50	1.22	1.14	1.096	1.0	1.05	.76
Nozzle Control	2.33	2.33	2.10	2.13	2.05	2.17	1.53	1.52
Stator Gen	2.43	2.55	2.40	2.43	1.52	1.20	1.35	1.02
Fuel Oil Cooler	1.71	1.71	1.12	1.04	1.35	1.59	1.18	1.53

(b) Dollars

Component	Current		Simple		Current		Refined	
	1982	79-82	1982	79-82	1982	79-82	1982	79-82
Main Fuel Pump	1.50	1.50	1.41	1.36	5.88	4.09	3.59	3.0
N2 Sensor*	2.0	2.0	1.77	1.72	2.25	2.48	2.20	2.41
Nozzle Control*	2.0	2.0	.856	1.77	10.1	16.8	6.28	9.97
Stator Gen	1.67	1.67	1.60	1.40	5.21	4.63	5.21	4.63
Fuel Oil Cooler	1.25	1.25	.623	.725	5.62	2.25	5.62	2.08

*Costs averaged for two different intervals which are in use

Table XXII
Savings From Graphic Interval Determination (Percent)

(a) Availability

Component	1982 Simple	1982 Refined	1979-1982 Simple	1979-1982 Refined
Main Fuel Pump	5.2%	23.1%	22.9%	7.9%
N2 Sensor	18.6	10.0	4.2	24.0
Nozzle Control	9.9	19.4	25.4	31.7
Stator Generator	1.2	10.9	11.8	15.0
Fuel Oil Cooler	34.5	13.3	12.6	3.7

(b) Dollars

Component	1982 Simple	1982 Refined	1979-1982 Simple	1979-1982 Refined
Main Fuel Pump	6.0%	38.9%	9.3%	26.7%
N2 Sensor	11.5	6.1	14.0	2.8
Nozzle Control	57.0	18.8	11.5	40.7
Stator Generator	4.4	10.2	16.2	DFR
Fuel Oil Cooler	50.2	-	42.0	7.6

Second, the failure data transformations are simple, and direct, given a complete set of failure data or a known failure distribution and basic cost information. One problem is that current failure ages are engine operating age, not actual component age. When the failure sample is incomplete, its direct plotting may be of use to identify a distribution. However, for small or significantly truncated samples, it may be necessary to construct a TTT plot based on the full failure distribution. The procedures for doing so have been demonstrated here. Their accuracy is dependent on several factors. These include (1) the uncertainty, bias, and inaccuracy in the data; (2) inaccuracy in plotting and estimating the parameters of the failure distribution; (3) inaccuracy in figuring the ages and time on test for the curve fit; and (4) inaccuracy in constructing the TTT plot. The repeatability of this procedure was checked by re-doing sets of calculations several times and indicated less than five percent difference through the process.

The cost data transformation also involves imperfections beginning with cost data inputs and assumptions. A certain amount of rounding error occurs in tabulating these statistics, converting cost elements to consistent units, (i.e. dollars), normalizing cost totals to cost per

event, and computing the standard cost. These results were consistently repeated to within one percent, using the D056 and K051 data.

Interval determination is a fourth step in which some error is introduced. Drawing the cost-tangent line and estimating the point (i/n*, U*) was repeated with less than two percent differences. Repeat calculations of the optimal interval T* ranged up to four percent off on smaller plots, and about two percent on 8 x 10 sized graph paper. A number of standard costs exceeded 2.5, requiring a horizontal scale running beyond the graph paper.

The cost comparisons involve the combined uncertainty of C, i/n, and U. The chain of manual calculations to fine $(C + i/n)U_i$ was repeatable within about three percent, given the use of three significant digits.

The assumptions used in the graphic technique include that of instantaneous, homogeneous failure of a single cell component, which for a real component poses several questions. How is failure to be defined? How will failure modes be considered? How can component strategies be aggregated into a system strategy? These are questions which further research might address.

Considerable savings may result from graphic interval determination. They range from three to about

forty percent reductions in down time and three to fifty percent reductions in dollar costs for the components studied here. The cumulative uncertainty of intervals and costs appears to be ±5% or less, apart from quality of the cost and failure data. This case study thus tends to support the need for and credibility of graphic interval determination.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The objective of this thesis is to demonstrate the use and benefits of a graphic procedure for determining replacement intervals. The approach was to use this technique in a case study of five F100 engine components. The results include (1) development of a graphic procedure which uses existing information, (2) a discussion of practical considerations in its application, and (3) estimates of quantitative cost reductions or readiness improvements which could be gained using the graphically determined intervals for each of the F100 components.

In conclusion, the results of this study underscore the potentially great benefits in use of the graphic technique. It is useful with existing information, but quality of age at failure data is a limiting factor, which is worth improving. The graphic technique is adaptable to whatever objective or cost measures are used. The failure data is generally from a truncated sample, and thus requires estimation of failure distribution parameters. Costs for the F100 components are dominated by material costs, i.e. mishaps, overhauls, and spare parts, so the optimization of age replacement strategy is especially important to cost-effective engine management for the F100.

Significant improvements in readiness and reduced

costs are possible if the graphic solution technique is effectively used for the F100. The estimated intervals and savings based on 1982 data are as follows:

(a) Dollar Cost Objective	Present Interval	Proposed Interval	Savings Pct	1982 Savings $
Main Fuel Pump	680	delete	39	2,720,000
N2 Sensor	1000/1500	900	6	82,000
Nozzle Control	750/900	1100	19	498,000
Stator Generator	2000	1500	10	101,000
Fuel Oil Cooler	1250	1250	0	-
				3,401,000

(b) Availability Objective	Present Interval	Proposed Interval	Savings Pct	1982 Savings ACFT NMC hr
Main Fuel Pump	680	delete	23	517
N2 Sensor	1000/1500	850	10	132
Nozzle Control	750/900	1100	19	132
Stator Generator	2000	900	11	78
Fuel Oil Cooler	1250	600	13	52
				911hr

These figures are developed from a small data base so more failure ages and a representative sample would be desirable to support these interval changes. However, the savings of $3.4 million and 38 aircraft down-days over a year, for just five components, indicate the large cost reductions that are possible.

The benefits above are direct improvements in an objective. There are additional benefits in streamlining the analysis process. Interval determination needs only failure data, so it is much faster than age exploration, with greater confidence of finding a minimum cost interval. The graphic procedure is quickly, easily repeated to meet the needs changing design, usage, and operating location. The graphic approach can, for the first time, directly relate intervals to improving cost or readiness objectives.

The procedures for data reduction, constructing TTT plots, and defining standard costs can be easily programmed for computer solution. Mathematical programming methods can possibly be used to optimally aggregate the individual intervals for a set of components.

The same graphic technique could also be used as a manual procedure by 3 or 5 level technicians at base or wing level to adapt intervals to the local operating environment. Hence, the graphic technique can serve as both a standard and a way to simplify the development of maintenance requirements.

Recommendations

It is relevant then, to consider what efforts are necessary to effectively use graphic interval determination for engines. One important need is improved age at failure data for components. This should reflect age of the

component, rather than engine, and tracking of failure modes so that preventable failures can be distinguished. These capabilities depend on engine diagnostics - capabilities of inspection, test, tracking, and event detection, being developed in the integrated turbine engine monitoring system (Integrated TEMS) program, and the associated data base which is to be maintained in the D042 CEMS.

A second need is for further development of graphic techniques for interval determination. A method is needed to define age replacement limits in cycles (which would require failure data in cycles). Capability is needed to graphically determine periodic inspection intervals. Existing methods can be applied to optimally aggregate the intervals and tasks for sets and multiple levels of components. Together with the procedure described here, these capabilities will be sufficient to structure an engine maintenance program. As demonstrated here, the graphic method is useful with failure distributions as well as data, so it is useful throughout the engine life cycle.

A third effort needed is to begin the use of a graphic technique in RCM analysis to set age replacement limits. Presently, no standard requirements or guidelines are provided under RCM. The graphic technique enables direct estimation of RCM benefits.

Thus it directly indicates whatever net benefits of RCM may occur

A final need is for clear management support of these initiatives. To this point, RCM for the F100 has been a multimillion dollar analysis program which offers no assurance of savings in either engine availability or readiness. Graphic interval determination supplies the missing element which is needed to assure a cost effective preventive maintenance program. Its use may well offer savings of millions of dollars and thousands of aircraft down hours per year as compared to the current program. The management actions recommended include:

(1) Arrange for the necessary data acquisition, (thirty or more ages at failure in a year for higher priority components and modules) and support of the Integrated TEMS and CEMS capabilities which are in development.

(2) Assignment of an Air Force engineer and program manager to integrate graphic interval determination with the RCM program foran engine in development, perhaps the F100 (F-15, F-16) or F101 (B-1) engines.

(3) Establish an initial program to use the graphic technique for determining age limits, of engine parts on the F100 and/or F101 engines. Use of graphic methods can be expanded to include periodic inspection as

the capability becomes available.

(4) After the pilot program, a graphic method of setting age replacement limits should be incorporated as a requirement in the relevant engine management guidance. This includes AFR 800-30 on development of military aircraft gas turbine engines, AFLC/AFSCR 66-35 and MIL-R-5096D on RCM, and the military standard which defines the engine structural integrity program (ENSIP).

APPENDIX

Summary of Data Collected

This appendix describes in further detail the data collected for this research project. The source of ages at failure and related narrative was the F100 SR report. An example is shown in figure A-1. Table A-1 shows the ages at failure used for each component, for calendar year 1982 and cumulative for the years 1979 through 1982. The failure modes for each component were classified to check proportions and age patterns. These are listed in Table A-2.

Cost data was obtained from the D056-B006, K051-YN3, K051-YN4, and D160B-D07 reports, illustrated in figures A-2 through A-5. These reports are available from Headquarters AFLC/LOEP for those who may want to use them. The cost element totals extracted from these reports are given in Table A-3. The cost of failure was normalized to cost per thousand failures, dividing cost element totals in Table A-3 by the number of failures given in Table A-3. This gives the normalized costs per 1000 failures listed in Table A-4. These costs can then be converted into down-time or dollar equivalents as was shown in the text.

```
ORDER NUMBER 830531-145746-E001    -001-007          PAGE 70     SET 29 WITH 264 OF 264 ITEMS

MIP NUMBER:                       AS210 E0 0884
ACTION AND REPEAT MIP:            RP AS210 E9 0025
INVESTIGATION REPORT NARR 80/11/19 REPEAT MIP AS210 E9 0025, MAIN FUEL PUMP
SPO STATUS:                       80/11/19 CLOSED BY MIPRB

ITEM 129

ACCESSION NUMBER:                 90118
REPORT CONTROL NUMBER:            80 0354 C1 361F
DATE DISCOVERED:                  80/10/06
NOMENCLATURE:                     MAIN FUEL PUMP
PART NUMBER:                      50526A10
SERIAL NUMBER:                    ABE0565
OPERATING TIME:                   561.4 HRS
ESTIMATED CORRECTIVE COST 23,510.00
DETAILS:
                                  DURING AUGMENTOR OPERATION IN FLIGHT WINGMAN NOTIFIED PILOT OF INCIDENT AIRCRAFT THAT SPARKS AND FLAMES
                                   WERE COMING OUT OF THE NUMBER 2 ENGINE AT THE 4:30 POSITION. AT THAT TIME PILOT TERMINATED AUGMENTOR
                                   OPERATION. VISUAL INSPECTION IN FLIGHT BY WINGMAN REVEALED A LARGE HOLE BURNED THROUGH THE RIGHT SIDE
                                   OF THE NUMBER 2 ENGINE AUGMENTOR, AND PIECES OF METAL PROTRUDING FROM THE AIRCRAFT IN THE SAME AREA.
                                   THE PILOT RTB WITHOUT INCIDENT AND SHUT THE NUMBER 2 ENGINE DOWN AND LANDING ROLL. POST FLIGHT
                                   INSPECTION REVEALED A LARGE HOLE BURNED THROUGH THE NUMBER 2 ENGINE AUGMENTOR AT THE 3 O'CLOCK
                                   POSITION. SEVERAL CONVERGENT SEGMENT LINERS EXHIBITED BURNING ON THE AFT TIPS NOT IN THE VICINITY OF
                                   THE BURN THROUGH. THERE WAS BURN DAMAGE TO THE AIRCRAFT FARING AND THE HORIZONTAL STAB. THE ENGINE WAS
                                   REMOVED AND RETURNED TO THE JEIM FACILITY FOR FURTHER INSPECTION. THE AUGMENTOR AND COMBUSTION CHAMBER
                                   DUCT WERE REMOVED. THE AUGMENTOR DUCT SEAL ASSEMBLY AND THE CONNECTING LINK-HINGED BALANCE NOZZLE
                                   SEGMENTS WERE INSPECTED. SPECIFIC CAUSE OF THE DAMAGE COULD NOT BE DETERMINED. SOME DAMAGE TO THE
                                   AUGMENTOR COMBUSTION CHAMBER DUCT SEAL ASSEMBLY WAS NOTED. IT COULD NOT BE DETERMINED IF THIS DAMAGE
                                   WAS PRIMARY OR SECONDARY TO THE BURING ACTION. WITH THE AUGMENTOR REMOVED THE FLAMEHOLDER GIVES THE
                                   APPEARANCE OF BEING WARPED AND COCKED TO ONE SIDE.
MIP NUMBER:                       AS210 E0 0947
ACTION AND REPEAT MIP:            RE AS219 E0 0945
INVESTIGATION REPORT NARR 80/11/19 REPEAT MIP AS210 E0 0945, MAIN FUEL PUMP
SPO STATUS:                       80/11/19 CLOSED BY MIPRB

ITEM 130

ACCESSION NUMBER:                 90144
REPORT CONTROL NUMBER:            23027 C2 561T
DATE DISCOVERED:                  80/10/19
NOMENCLATURE:                     MAIN FUEL PUMP
PART NUMBER:                      50529
SERIAL NUMBER:                    ABE 1771
OPERATING TIME:                   114.5 HRS
ESTIMATED CORRECTIVE COST 23,540.00
DETAILS:
                                  DURING MAIN FUEL PUMP SPOOL DOWN TEST PF2 PRESSURE AT 12.5 PERCENT PRNR WAS 285 PSI. MINIMUM PRESSURE
                                   IS 310 PSI. TEST WAS PERFORMED AFTER ENGINE MONITORING AND IDLE RUN. PF2 PRESSURE WAS 340 AT 40
                                   PERCENT DURING START. REMOVED AND REPLACED MAIN FUEL PUMP.
MIP NUMBER:                       AS210 E0 0915
```

Figure A-1: Example of F100 Service Report (SR)

Table A-I
Age at Failure Data

(a) Ages at Failure, CY 1982

Main Fuel Pump	N2 Sensor	Nozzle Control	Stator Generator	Fuel Oil Cooler
4	49	6	192	468
16	178	77	194	471
51	179	127	237	557
70	215	476	360	
87	250	797	888	
146	281	805	968	
206	359	941		
211	379			
305	647			
321	661			
416	721			
425	742			
625	807			
	825			
	907			

(b) Ages at Failure, CY 1979–1982

Main Fuel Pump		N2 Sensor		Nozzle Control	Stator Generator	Fuel Oil Cooler
4	218	2	597	77	33	35
5	231	5	620	127	192	313
16	233	49	635	133	194	468
28	305	128	647	157	224	471
51	321	133	647	278	237	575
77	321	133	661	279	244	584
80	366	179	663	281	280	722
87	375	215	692	476	360	847
96	416	250	695	719	449	995
105	424	250	721	746	450	
110	425	287	728	797	501	
110	468	359	742	805	520	
122	480	360	794	873	646	
129	493	379	807	941	673	
146	494	383	825		682	
157	514	393	876		711	
179	558	405	882		798	
184	561	408	907		888	
206	562	429	1019		968	
211	612	439				
	625	588				

Table A-II

Primary Component Failure Modes

Component and Failure Mode	Ages at Failure, 1979-82
1. Main Fuel Pump	
a) N2 Shaft Failure	122,233,468,548,661
b) Wear-vane, seals, bearings	(4),140,146,206,366,416, 494
c) Internal Binding/LowFlow	110,179,211,296,305,321
d) Foreign Object Damage (FOD), vane fracture/ seizure	80,87,129,157,184,231, 321,375,494,562,612,625
Other modes: Internal Binding/High Flow; Leakage; Cracked Housing, Calibration off/ Sheared P screw.	
2. N2 Sensor	
a) Sheared Sensor Shaft and/or Shaft Screws	128,360,383,439,597,620, 635,664,692,695,721,728, 825,907
b) Internal Failure	359,429,588,647,661,882
c) Calibration Off	2,40,133,133,742,789,876
3. Nozzle Control	
a) Internal Binding servo failure	746,797,805,873,941
b) Internal Binding-Drives air motor, bearings	0,7,10,77,157,281
4. Stator Generator	
a) Internal Failure-windings sheared/stripped screws	192,224,237,244,450,501, 672,682,711,798
b) No Output-disengaged or cracked cannon plugs	280,449,646,888
c) Cracked Housing, welds, or mount coupling	33,194,360,520,968
5. Fuel Oil Cooler	
a) Internal Failure-burst due to overpressure	3,8,722,745,947,964
b) Cracked Housing, mount, or welds	0,35,468,471,584,847, 995

MAINTENANCE ACTIONS, MANHOURS, AND ABORTS BY WORK UNIT CODE \ * A11* 82/04/20 Q-D056B-B06-RX-256 PAGE 151
PERIOD ENDING 82MAR31 RCS: LOG-LOE(AR)7170
ALC: WRALC TYP EQP: ACF EAD: F015 WUC: 23HAD

WUC NOUN	MONTH	INV	OP TIME	ABO	----MAINT ACTION--- FAIL	OTH/MAL	TOT	------MTBM----- TYPE-1	TOTAL	-------MANHOURS------- SCHED	UNSCH	SHOP	-SHOP ACTION UNITS- REPR	CONDM	NRTS
23HAD PUMP FUEL MAIN	MAR	361	6490	1	12	3	39	988	228	175	399	12			
CAT QPA ACT LMT USE FACT	FEB	363	6897	1	15		75	1256	239	323	1277	545			2
B 2 469 1.00	JAN	356	5887		12	3	55	1270	229	100	686	781			1
	DEC	370	6685	1	4		33	1766	266	107	582	1219			4
	NOV	266	5209		12	3	67	1609	202	155	1055	265	1		
	OCT	382	7529		6	1	58	1945	231	91	649	2633			
	TOTALS		38697	3	61	10	327	1269	237	951	4648	5455	1		7
23HAE PUMP FUEL AUGMENTOR	MAR	361	6490		2		2	6425	1606		24				
CAT QPA A T LMT USE FACT	FEB	363	6897		2	5	9	5563	1442	1	91	1			1
B 2 364 1.00	JAN	356	5887	1	2	7	13	5081	1695	9	91	2			
	DEC	370	6685		3	1	5	7770	2158	3	56				
	NOV	266	5209		2		3	18498	2176		101				
	OCT	382	7529			1	10	7778	1496		143				
	TOTALS		38697	1	11	14	42	7036	1843	13	506	3			1
23HAF CONTLR F PUMP AUG	MAR	361	6490				1	4283	1205	8					
CAT QPA ACT LMT USE FACT	FEB	363	6897		5	1	17	2291	847	8	234	132			1
B 2 1.00	JAN	356	5887		4	2	14	1617	697		86	52			
	DEC	370	6685		8	1	15	2045	863		219	105			1
	NOV	266	5209		10	1	22	2312	925	3	222	142	1		
	OCT	382	7529		1		8	2288	1178	1	103	285			
	TOTALS		38697		28	5	77	2764	1005	20	864	716	1		2
23HAG SENSOR HYDMECH N2	MAR	361	6490		11		18	918	406	10	141				
CAT QPA ACT LMT USE FACT	FEB	363	6897		18	1	64	1025	371	108	205	144			
B 2 205 1.00	JAN	356	5887		13	2	33	988	356	50	238	17			
	DEC	370	6685		7	1	28	1050	360	30	155	108			2
	NOV	266	5209	1	16	2	39	925	333	33	329	51			1
	OCT	382	7529	3	14	3	21	997	347	8	284	204			
	TOTALS		38697	4	79	9	203	980	381	239	1352	524			3
23HAH SENSOR TEMP FAN EX	MAR	361	6490		6	1	11	2142	1015	4	70				
CAT QPA ACT LMT USE FACT	FEB	363	6897		11	1	19	2996	1145	10	201	490	1		
B 2 369 1.00	JAN	356	5887		1		8	3952	1147	7	52	736			
	DEC	370	6685		1		7	3885	1079	2	44				
	NOV	266	5209		7		16	3700	881	20	137	665			
	OCT	382	7529		2	2	13	2992	845	9	87	900			
	TOTALS		38697		28	4	74	2764	1046	52	591	2791	1		
23HAK THERMOCPL FAN TIT	MAR	361	6490		7		10	1752	1071		89				1
CAT QPA ACT LMT USE FACT	FEB	363	6897		7	1	16	2163	829	1	86				
B 2 595 1.00	JAN	356	5887		8	2	10	2371	697	15	94				
	DEC	370	6685		3		21	2428	747		94	1			1
	NOV	266	5209		4	3	20	1682	804		161				
	OCT	382	7529		9	1	11	1389	845		82				
	TOTALS		38697		38	7	88	2037	880	16	606	1			2

Figure A-2: Example of D056-B006 Report: failures, aborts, and manhours

WEAPON SYSTEM F015A WRALC
AFM 65-110/66-1 DATA AS OF 83 MAR

SYSTEM AVAILABILITY MODEL
WORK UNIT CODE STATUS
LOG-LO(Q)7954

Q-K051.-YN3-QT-MYN PAGE
DATE PROCESSED 83 MAY 01

WUC	NOUN	CAT IND	FORCE DEGRADATION CONTRIBUTION: CURRENT QTR RANK	CURRENT QTR PERCENT	1ST PREV QTR RANK	1ST PREV QTR PERCENT	2ND PREV QTR RANK	2ND PREV QTR PERCENT	3RD PREV QTR RANK	3RD PREV QTR PERCENT
03XXX				0.263		0.232		0.286		0.298
04XXX				0.165		0.406		0.279		0.173
11XXX				0.914		1.324		0.948		0.920
12XXX				0.662		0.351		0.465		0.243
13XXX				0.977		1.373		1.054		0.706
14XXX				2.785		3.316		1.397		3.858
23XXX				3.295		2.880		2.098		2.076
24XXX				5.040		6.841		3.515		2.224
41XXX				0.537		0.627		0.653		0.361
42XXX				0.749		0.624		0.486		0.513
44XXX				0.103		0.172		0.124		0.238
45XXX				0.916		1.076		1.173		0.841
46XXX				1.853		3.539		6.561		4.342
47XXX				0.048		0.060		0.052		0.013
49XXX				0.092		0.103		0.152		0.216
51XXX				0.328		0.323		0.245		0.093
52XXX				0.364		0.311		0.226		0.371
55XXX				0.049		0.013		0.035		0.019
57XXX				0.075		0.109		0.023		0.029
63XXX				0.230		0.339		0.129		0.189
65XXX				0.344		0.122		0.079		0.119
71XXX				0.319		0.374		0.315		0.173
74XXX				2.009		2.399		1.522		1.150

Figure A-3: Example of the K051-YN3 Report

WEAPON SYSTEM F015C WRALC
AFM 65-110/66-1 DATA AS OF 82 JUN

B04
SYSTEM AVAILABILITY MODEL
WORK UNIT CODE COMPUTATION DATA
LOG-LO(Q)7954

Q-K051.-YN4-LQ-MYN PA
DATE PROCESSED 82 AUG

NOTE - WORK UNIT CODES RANKING FOR THE FIRST TIME ARE INDICATED BY AN ASTERISK.

WUC	NOUN	CAT IND	QPA	SPEC INV	UNSCHED NMCM HRS	NMCS HRS	UNSCHED NMCB HRS	BFA	IFA	SCHED MAINT HRS	UNSCHED MAINT HRS	OLI WUI
23BXX					2.0	0.0	0.0	0	0	135.7	1764.6	
23F00	AUG DUCT/NOZZLE MOD	B	2	0	149.0	4.0	5.0	0	0	171.2	3716.9	
*23FA2	LINER AUG CON N FLP	B	2	0	57.0	2.0	0.0	0	0	0.0	50.8	
23FA3	LINER AUG CON N SEL	B	2	0	1.0	0.0	0.0	0	0	1.0	64.0	
*23FA4	CAM FOLLOWER	B	2	0	0.0	0.0	0.0	0	1	0.0	70.2	
*23FAA	DUCT AUG COMB CHAMB	B	2	0	1.0	0.0	2.0	0	0	24.0	295.7	
23FAB	LINER AUG COMB CHAM	B	2	0	21.0	50.0	39.0	0	0	54.8	1250.2	
*23FB2	SHAFT FLEX ACT DIV	B	2	0	0.0	0.0	0.0	1	0	4.0	12.0	
23FBA	SEAL DIV NOZ SEG	B	2	0	43.0	10.0	0.0	0	0	5.5	489.9	
23FBC	NOZ SEG DIV AUG	B	30	0	151.0	0.0	0.0	0	0	1.5	378.2	
*23FBG	BRIDGE CLAMP	B	2	0	9.0	0.0	0.0	0	0	0.0	26.1	
*23FCA	SHAFT FLEX SEC ACT	B	2	0	0.0	0.0	0.0	1	0	0.0	16.0	
23FXX					432.0	66.0	46.0	2	1	262.0	6370.0	
*23GC0	PUMP ASSY MAIN OIL	B	2	0	11.0	0.0	0.0	0	0	0.0	0.0	
23GE0	FILTER ASSY OIL	B	2	0	21.0	3.0	0.0	0	0	0.0	33.0	
23GXX					32.0	3.0	0.0	0	0	0.0	33.0	
23H00	FUEL SYSTEM	B	1	0	233.0	25.0	17.0	0	0	0.2	130.1	
23HAA	CONTL UNIF TURB ENG	B	2	0	177.0	57.0	33.0	0	0	54.0	2147.1	
23HAB	CONTL ENG ELECTR	B	1	0	1211.0	145.0	116.0	2	0	15.0	1568.0	
23HAD	PUMP FUEL MAIN	B	2	0	11.0	36.0	0.0	0	0	231.7	1129.6	
23HAF	CONTLR F PMP AUG	B	1	0	17.0	12.0	0.0	0	0	2.3	225.7	
23HAG	SENSOR HYDMECH N2	B	1	0	6.0	0.0	0.0	0	1	84.0	391.4	
23HAH	SENSOR TEMP FAN EX	[illegible]	1	0	320.0	44.0	0.0	0	0	11.9	714.9	
*23HAM	PROBE AUG PRESS PTG	B	2	0	61.0	0.0	0.0	0	0	0.6	10.8	
23HAN	VALUE FUEL PRES DMP	B	2	0	0.0	0.0	0.0	3	0	0.0	127.9	
23HAQ	VALUE SOL DERICHMNT	B	2	0	0.0	0.0	0.0	4	0	0.0	88.8	
23HXX					2036.0	319.0	166.0	9	1	399.7	6534.3	

Figure A-4: Example of the K051-YN4 Report

```
LO/VAMOSC                                          COMPONENT SUPPORT COST SYSTEM (CSCS)                     * D07 *               AS OF FY 82-4
PRODUCED 30 SEP 82        RCS HAF-LEY(AR)8107      TOTAL BASE WORK UNIT CODE (WUC) COSTS                MDS    F015A       0-D160B-DDC-AR-20C
                                                            MDS    F015A                                                         PAGE    900
             PRIMARY ACTIVE INVENTORY:    108       FLYING HOURS:    18,703      SORTIES:  14,030      LANDINGS:  14,076
                                                              TOTAL BASE COSTS
                      COMPONENT: $19,677.5       SUPPORT GENERAL:        $339.1        TCTO:       $46.5

 WUC 23MAC    NOUN NO MATCH                       QPA    0
 -----------------------------------------------------------------------------------------------------------------------------
   ---ON EQUIPMENT---   --OFF EQUIPMENT---    DIRECT     SUP MGT  2ND DEST     EXCH      EXCH      EXCH    CONDMN   MAT MGT          TOTAL
     LABOR   OV/HEAD     LABOR   OV/HEAD    MATERIAL    OV/HEAD     TRANS    REPAIR    MOD IV     MOD V    SPARES   OV/HEAD            WUC
      0.0       0.3       0.0       0.0         0.0        0.0        0.0       0.0       0.0       0.0       0.0       0.0           $0.3

 -------------------------------------------------MAINTENANCE DATA-----------------------------------------------------------
   OPERATING                                              ----------------MTBM----------------
       TIME     MMTR      RTS     NRTS  CONDEMNED         INHERENT  INDUCED   OTHER  NO DEFECT       --- NO OF MAINT EVENTS (ON EQUIP)---
      8,618        0        0        0          0                0        0       0          0       INHERENT  INDUCED   OTHER  NO DEFECT
                                                                                                            0        1       0          1
   ------NO OF MAINT MAN-HOURS (ON EQUIP)-------        ------NO OF MAINT MAN-HOURS (OFF EQUIP)------
   INHERENT  INDUCED   OTHER  NO DEFECT   TOTAL        INHERENT  INDUCED   OTHER  NO DEFECT    TOTAL
          0        0       0          4       4               0        0       0          0        0
 WUC 23MAD    NOUN                                QPA    2
 -----------------------------------------------------------------------------------------------------------------------------
   ---ON EQUIPMENT---   --OFF EQUIPMENT---    DIRECT     SUP MGT  2ND DEST     EXCH      EXCH      EXCH    CONDMN   MAT MGT           TOT'
     LABOR   OV/HEAD     LABOR   OV/HEAD    MATERIAL    OV/HEAD     TRANS    REPAIR    MOD IV     MOD V    SPARES   OV/HEAD              W
      9.0      48.5       0.2       0.0         0.0        0.1        0.0       4.0       0.0       0.0       0.0       0.8          $62.4

 -------------------------------------------------MAINTENANCE DATA-----------------------------------------------------------
   OPERATING                                              ----------------MTBM----------------
       TIME     MMTR      RTS     NRTS  CONDEMNED         INHERENT  INDUCED   OTHER  NO DEFECT       --- NO OF MAINT EVENTS (ON EQUIP)---
     18,703        8        1        2          0                0        0       0          0       INHERENT  INDUCED   OTHER  NO DEFECT
                                                                                                           35       10       1        158
   ------NO OF MAINT MAN-HOURS (ON EQUIP)-------        ------NO OF MAINT MAN-HOURS (OFF EQUIP)------
   INHERENT  INDUCED   OTHER  NO DEFECT   TOTAL        INHERENT  INDUCED   OTHER  NO DEFECT    TOTAL
        440       49       0        748   1,877               C        0      21         30       51
```

Figure A-5: Example of D160B-D07 Report, Component Support Costs

Table A-III

Cost Element Statistics

(a)Cost data for CY 1982

Cost Element	Fuel Pump	N2 Sensor	CENC	StatGen	Cooler
Occurrences					
Mishap, A	0	0	0	0	0
B	0	0	0	0	0
C	3	1	0	0	0
Aborts	7	7	4	12	1
Unsch Events	834	454	481	376	78
Maintenance					
Failures	177	166	160	242	42
Mal/Other	91	35	100	72	34
Total Events	925	489	581	404	112
A/C NMC hr	1004	771	569	345	371
% of engine	1.41	.76	1.535	.446	.477
% of A/C	.034	.0182	.037	.011	.0115
Eng Removals	7	3	2	1	0
Resource Costs					
Material					
#A/C Lost	.003	.001	0	0	0
Engine Ovhl	3	1	0	0	0
*Item Ovhl	177	166	160	242	42
Labor					
Flt Line Sch	2926	662	1582	128	103
Unsch	13817	2396	4927	1933	1587
Total incl shop	18192	3234	15749	2062	1708
*Depot	4250	1500	2250	2000	600
*Engine Op hrs					
Installed	89	83	54	24	4
Uninstalled	15	6	4	2	0
*Engine Fuel					
@3000 lb/hr	312000	267000	174000	78000	12000

*Derived using cost assumptions for component

(b)Cost data, CY 1979-1982

Cost Element	Fuel Pump	N2 Sensor	CENC	StatGen	Cooler
Occurrences					
Mishap A	0	0	0	0	0
B	5	3	2	0	0
C	12	8	1	4	1
Aborts	30	40	25	45	8
Unsch Events	3210	2043	2135	1549	457
Maintenance					
Failures	397	817	569	983	169
Mal/Others	319	97	350	221	137
Total Events	3611	2140	2485	1771	594
A/C NMC hr	5807	3523	2180	1649	797
% of engine	1.141	.817	.504	.352	.246
% of A/C	.041	.0294	.0183	.0127	.0089
Eng Removals	24	7	4	3	3
Resource Costs					
Material					
#A/C Lost	.50	.30	0	.20	0
Engine Ovhl	14	4	1.6	1.6	1.2
#Item Ovhl	397	817	569	983	169
Labor					
Flt Line Sch	12891	1203	569	583	478
Unsch	44053	15156	18025	9405	7942
Total Inc Shop	57264	20247	10087	25100	8795
*Depot	9750	8000	8250	9500	2400
*Engine Op hrs					
Installed	200	410	190	100	17
Uninstalled	50	15	10	10	7
*Engine Fuel @3000 lb/hr	750000lb	1275000	600000	330000	72000

Table A-IV

Costs per 1000 Failures

(a)CY 1982

Cost Element	Fuel Pump	N2 Sensor	CEMC	StatGen	Cooler
Occurrences	5.64	6.02	6.25	4.13	23.8
Mishap A	0	0	0	0	0
B	0	0	0	0	0
C	17	6.0	0	0	0
Aborts	40	42	25	49	24
Unsch Events	4704	2733	3006	1553	1856
Maintenance					
NMC A/C hr	5662	4640	3556	1425	8830
NMC engines	40	18	12.5	4.2	0
shop	23	12	12.5	4.2	0
depot	17	6	0	0	0
NMC items					
shop	-	-	-	-	-
depot	1000	1000	1000	1000	1000
Resource Costs					
Aircraft Loss	.210	.102	.025	.049	.024
Engines, base	23	12	12.5	0	0
ovhl	17	6	0	0	0
Items ovhl	1000	1000	1000	1000	1000
Labor					
Flight line	77900	14400	30970	7980	37770
shop	8170	1000	66000	-	-
depot	25000	10000	15000	10000	15000
Engine hrs	546	524	358	100	100
Fuel, 1000lb	1638	1572	1074	300	300

(b)CY 1979-1982

Cost Element	Fuel Pump	N2Sensor	CEMC	StatGen	Cooler
Occurrences					
Mishaps A	0	0	0	0	0
B	12.61	6.12	2.03	0	0
C	3.35	9.79	4.07	1.76	5.92
Aborts	76	49	46	23	47
Unsch Events	8290	2500	1800	3750	2700
Maintenance					
NMC A/C hr	14630	10715	6577	4747	3803
NMC engines					
shop	36.3	5.15	1.83	4.21	10.65
depot	24.2	3.42	1.22	2.81	7.10
NMC items					
shop					
depot	1000	1000	1000	1000	1000
Resource Costs					
Aircraft Loss	1.37	.759	.290	.040	.107
Engines, base	60.5	8.6	3.0	7.0	17.8
depot	24.2	3.4	1.2	2.8	7.1
Items ovhl	1000	1000	1000	1000	1000
Labor					
flight line	13500	7420	6070	9400	13370
shop	806	4750	100	7500	2220
depot	22500	9000	13500	9000	13500
Base Eng op hrs	573	570	337	108	114
Fuel, 1000 lb	1719	1530	1011	324	342

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AUTHOR'S BACKGROUND

Captain John R. Brill is a graduate of the University of Wisconsin-Madison, Bachelor of Science in Engineering Mechanics. He was commissioned May 1979 through Air Force ROTC. Prior to entering the Graduate Systems Management course, Captain Brill served as a systems engineer with the Deputy for Propulsion, Aeronautical Systems Division, at Wright-Patterson AFB. His duties included field problems analysis for the TF34 and F100 engines, engineering responsibility for automated test systems, Reliability Centered Maintenance (RCM) analysis, engine performance and trend analysis, and an 18-month study and systems analysis of inspection, test and tracking capabilities and experience for the J57, J79, J85, TF30, TF33, TF34, TF39, TF41, F100, F101 and fighter derivative engines. In this capacity, Captain Brill studied the design, tech data and support system for each engine.

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